Optical characterizations of epitaxial materials: from crystal defects to optoelectronic properties

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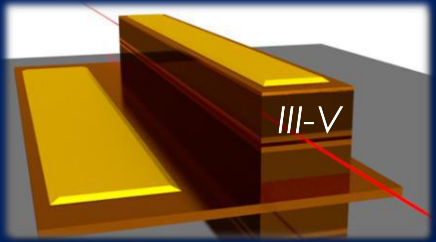
Introduction : Optical properties of materials

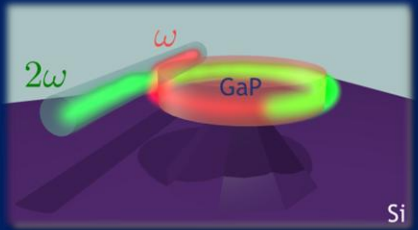
Photonic applications

Active photonics



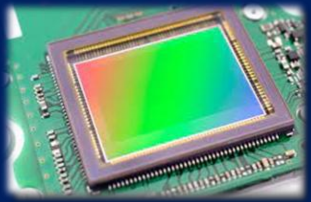
- Telecommunications, computing, medical imaging, defence, surgery, …

Passive photonics



- Optical communications, on-chip signal processing…

Sensors



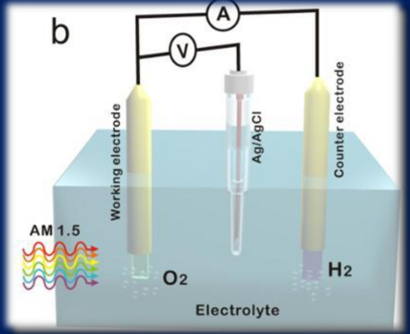
- Defense, agriculture, environement, gas detection, health…

Energy applications

Photovoltaics

- Sustainable low CO_2 emissions energy production, conversion of sunlight into electricity. …

Solar fuels



- Solar hydrogen production through water splitting, sun-assisted atmospheric carbon conversion into fuel…

Outline

I-Bandstructure of semiconductors, crystal defects and optical processes

-Bandstructures and semiconductors

-Crystal defects and their impact on optoelectronic properties

II-Characterizing light emission properties

-Photoluminescence

-Electro- & Cathodo-luminescence

III-Characterizing light absorption properties

-Absorbance measurements

-Ellipsometry & Photo-current

IV-Toward single photons sources

-micro-photoluminescence, g(2)

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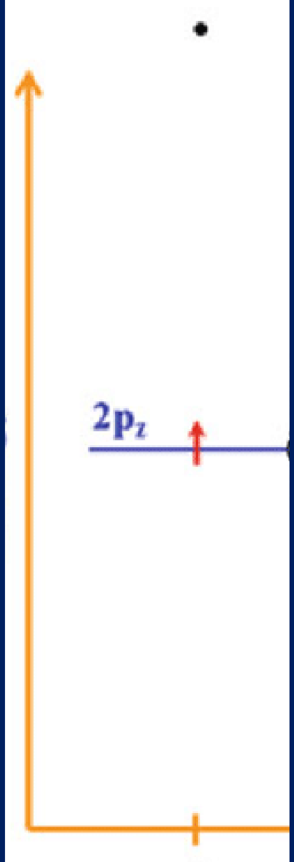
What is a bandstructure ?

→Linear chain of carbon atoms

CH_4 C_2H_4 C_4H_6 C_8H_{10} $C_{2n}H_{2n+2}$

Energy



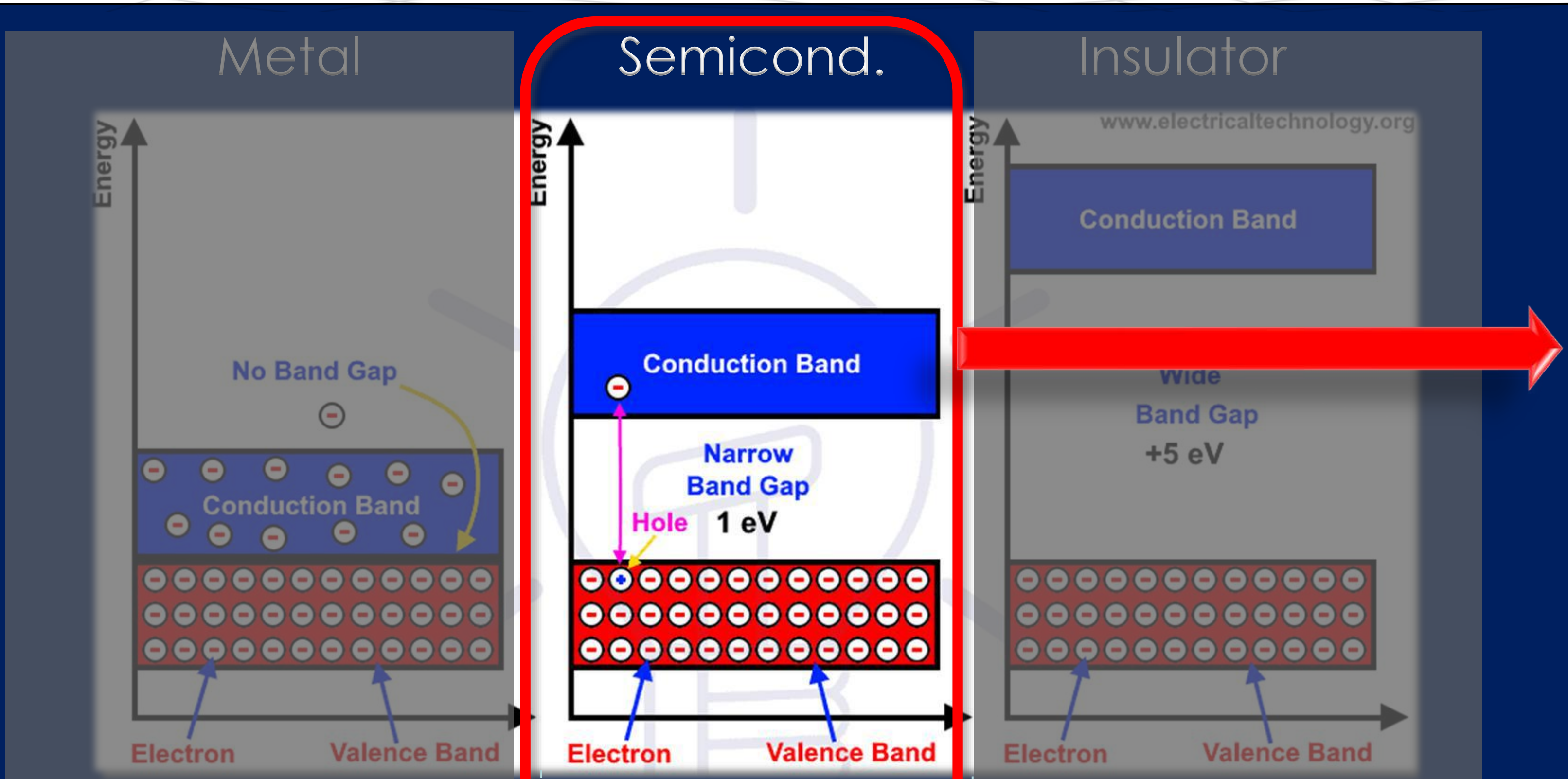
Conduction Band CB (empty)

Bandgap

Valence Band VB (filled)

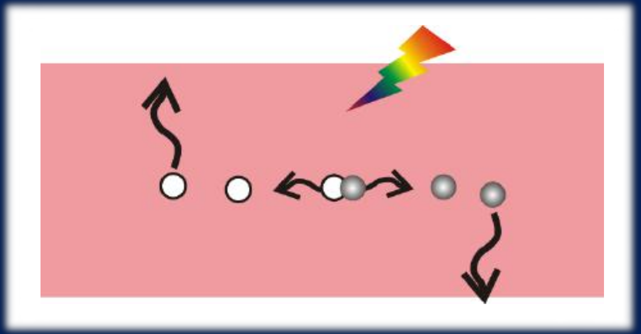
No. of carbon atoms

Band structure classifications



	Metal	Semicond.	Insulator
Electrical properties	✓	✓	✗
Optical properties	✗	✓	✓

Photonic or Photoelectric devices (e.g. PV, PEC, LEDs, lasers…)

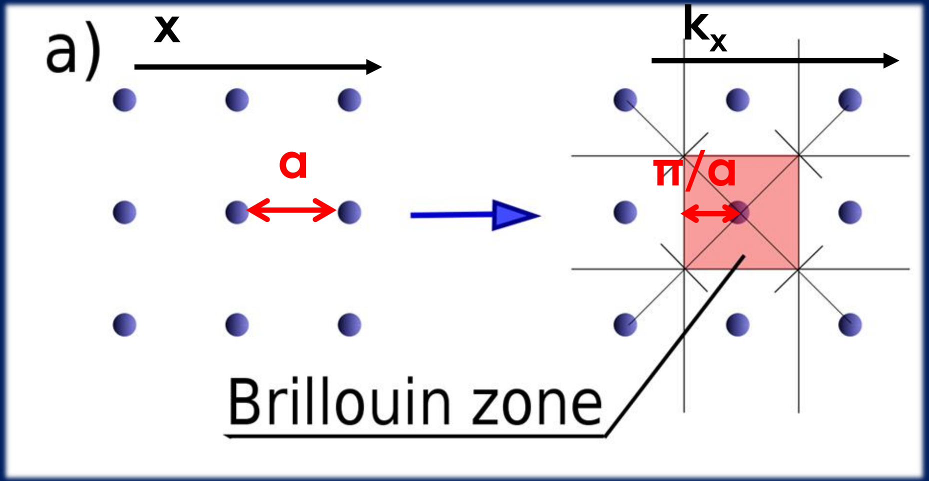


Requirements:

- Good light absorption or emission (α, f)
- Efficient charge separation or injection (p-n junction)
- Good transport properties (μ, L_D)

The Brillouin zone

2D square lattice



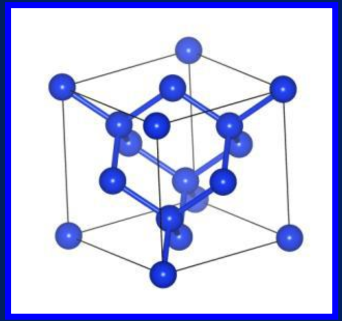
$$\psi(x+na)=\psi(x)$$

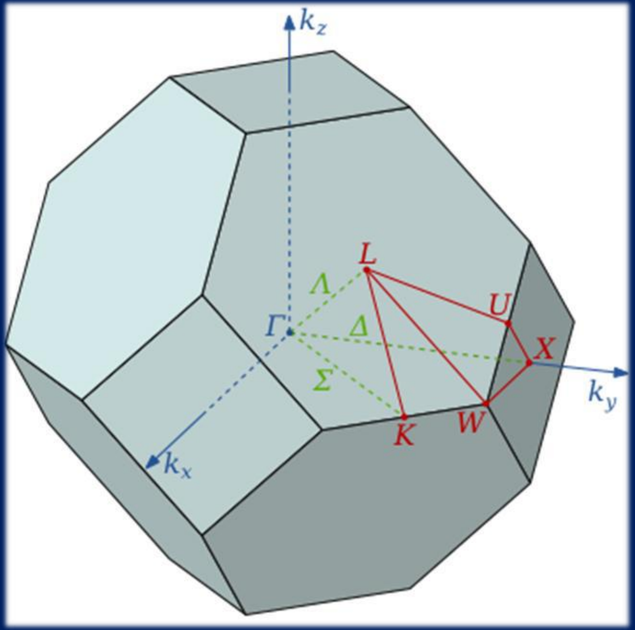
$$\psi(x+a)=e^{ika}\psi(x)$$

k = wavevector associated to phases of regular atomic orbitals in the crystal

3D crystal

Silicon : a diamond FCC structure



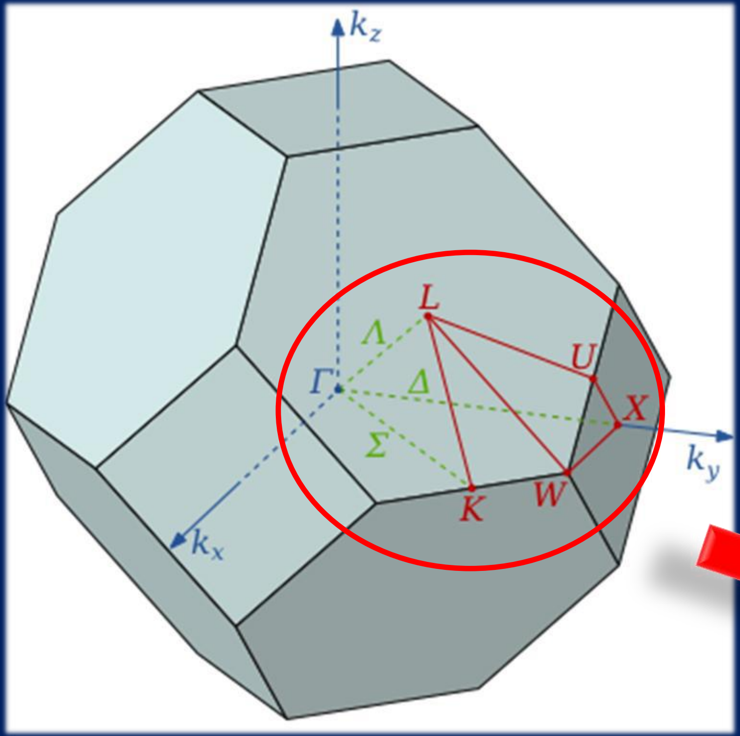


Different planes in the reciprocal space
→various periodicities of the 3D crystal

Any change of the lattice ordering, interatomic distance, nature of atoms, will change the properties in k-space and associated Energy levels.

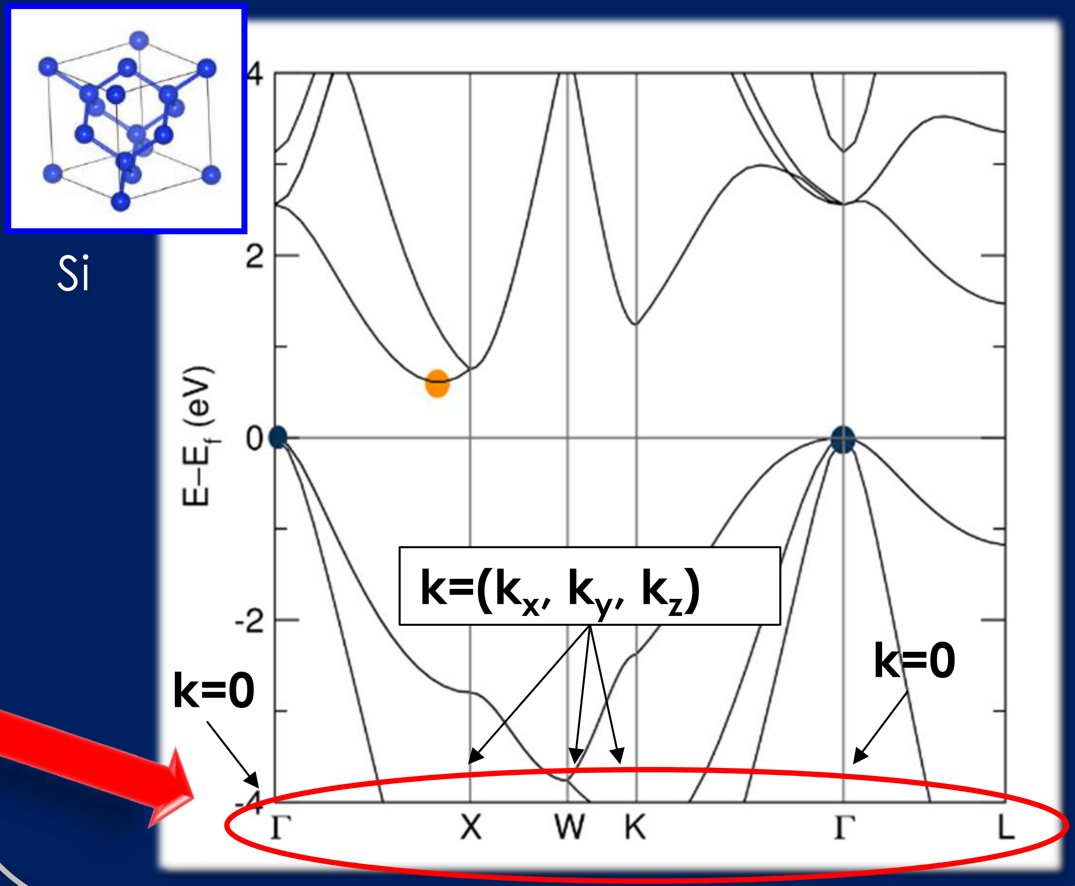
Bandstructures

From Brillouin zone …



First Brillouin zone of FCC lattice, a truncated octahedron, showing symmetry labels for high symmetry lines and points

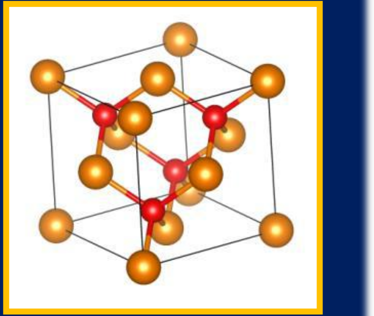
…To bandstructure



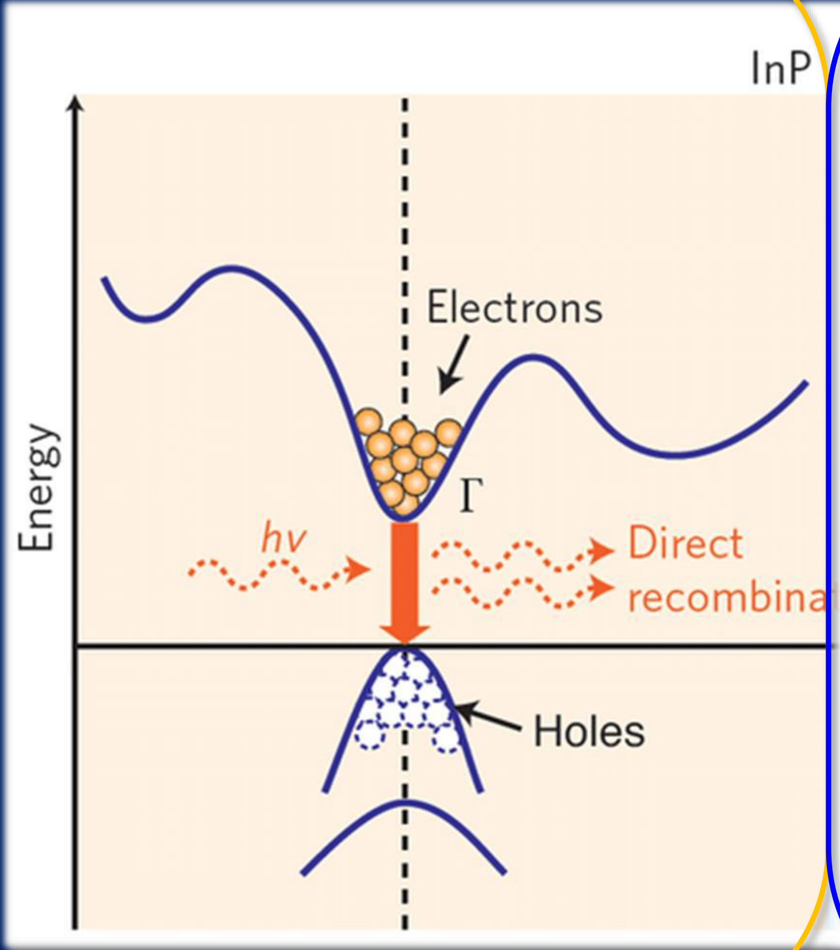
Bandstructures : specific paths in k-space

Direct vs Indirect bandgaps

Zinc-Blende structure

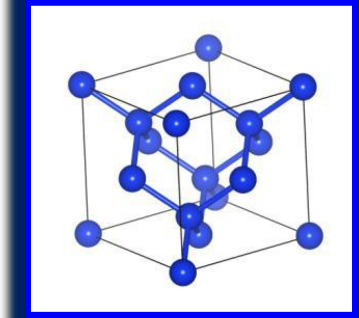


III-V FCC



Direct = optically efficient

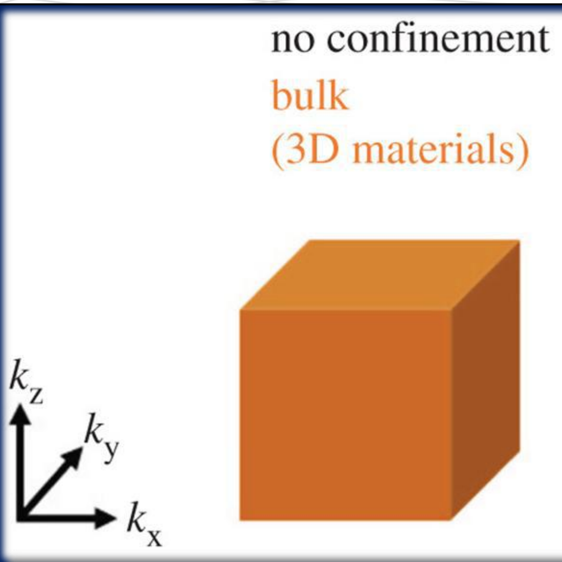
Diamond structure

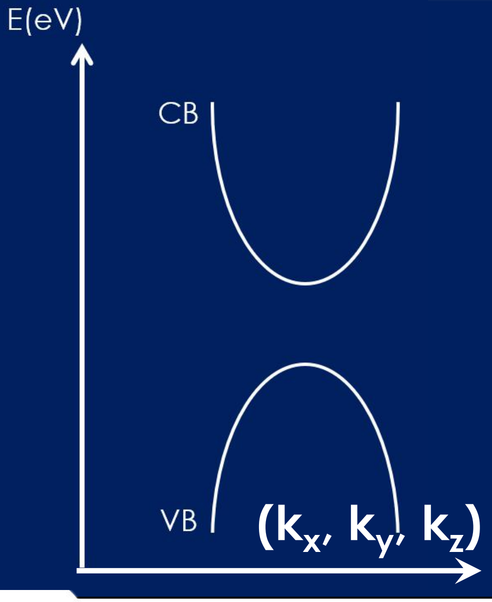


Si FCC

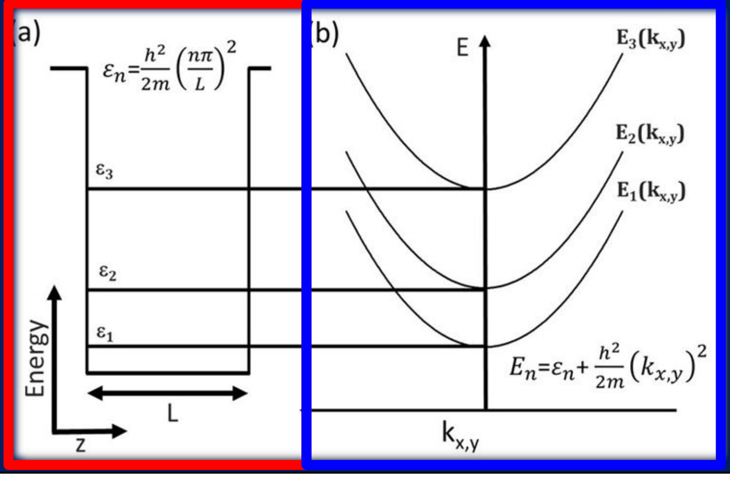
Indirect = optically limited

Quantum confinement & dimensionality

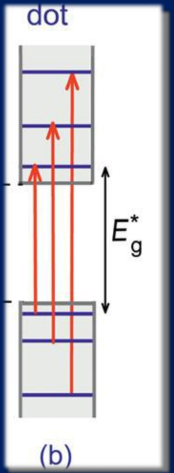


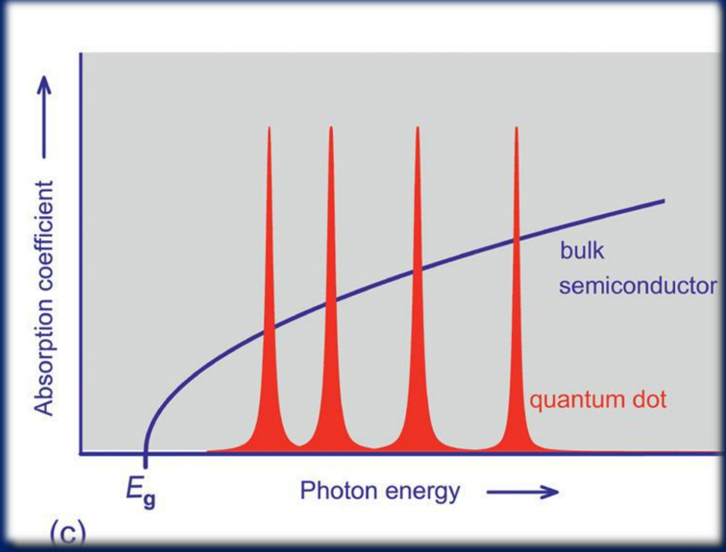


(k_z) (k_x, k_y)



(k_x, k_z) (k_y)





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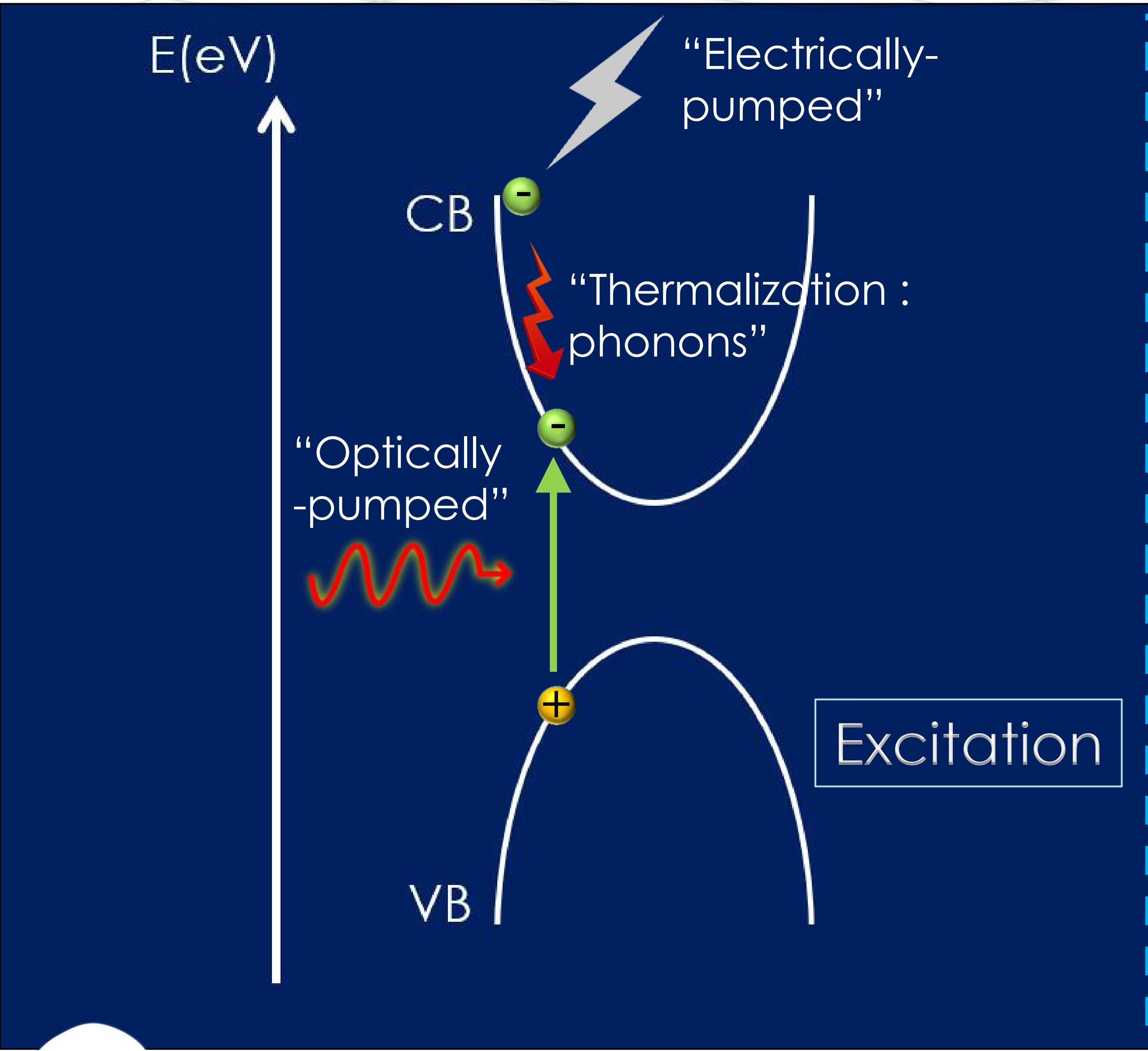
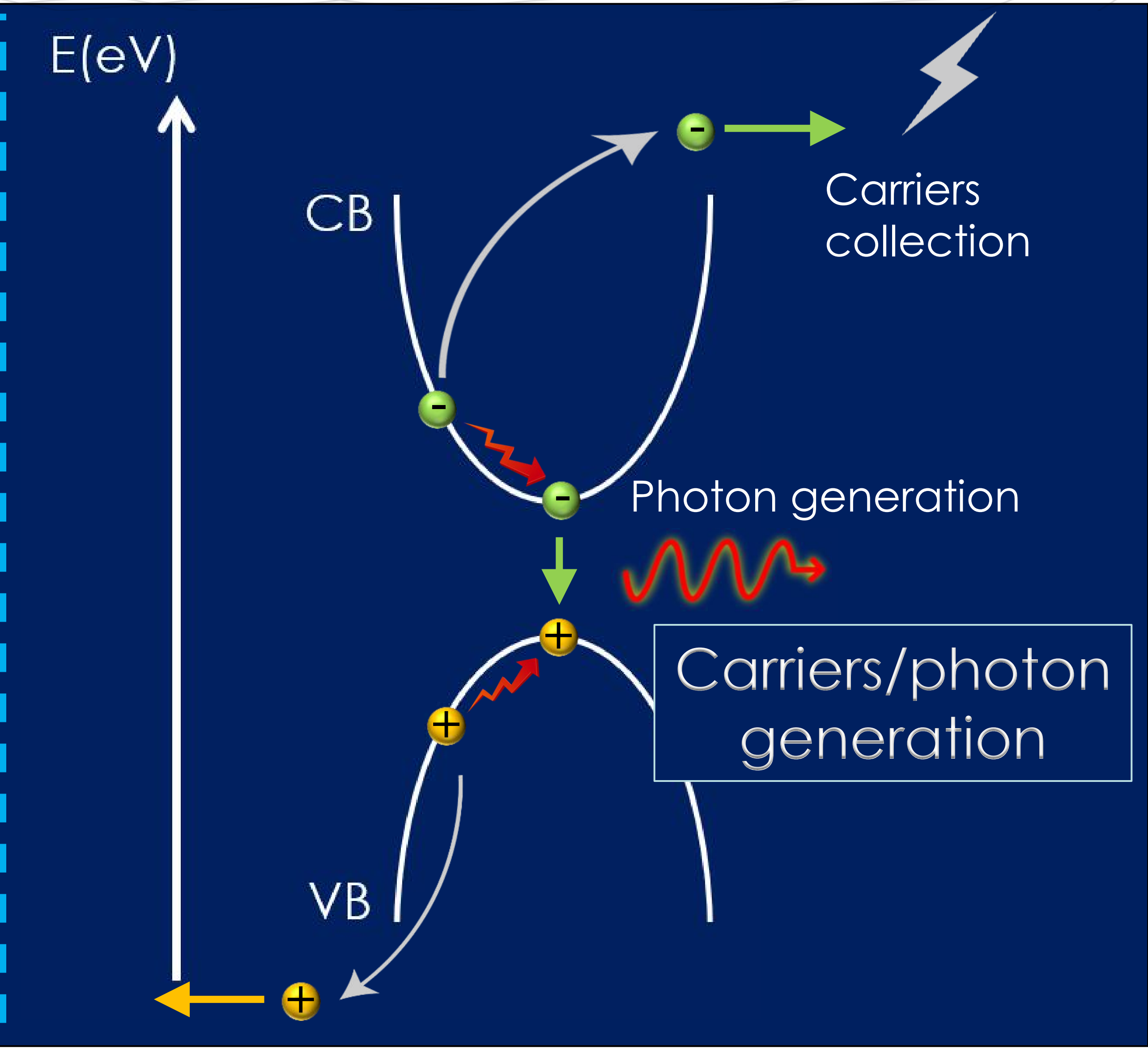
Ideal light-mater interactions in SC



Excitation

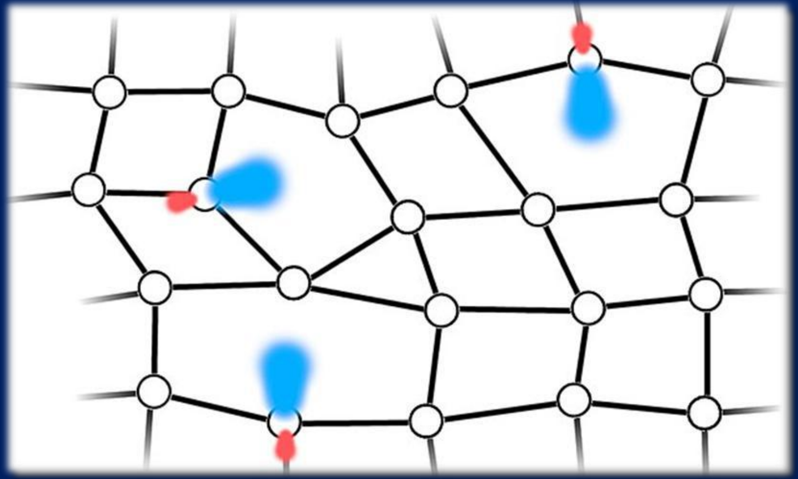


Carriers/photon generation

Proposed classification of crystal defects

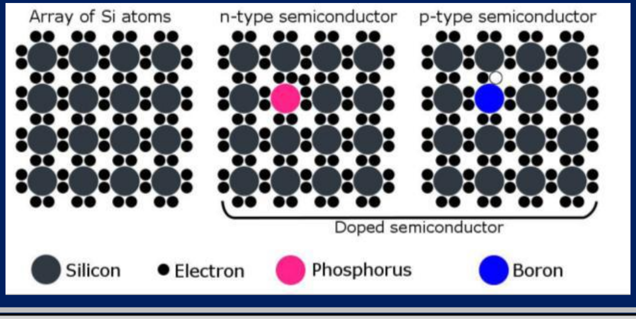
A dangling bond in a material is an unsatisfied valence on an immobilized atom

1



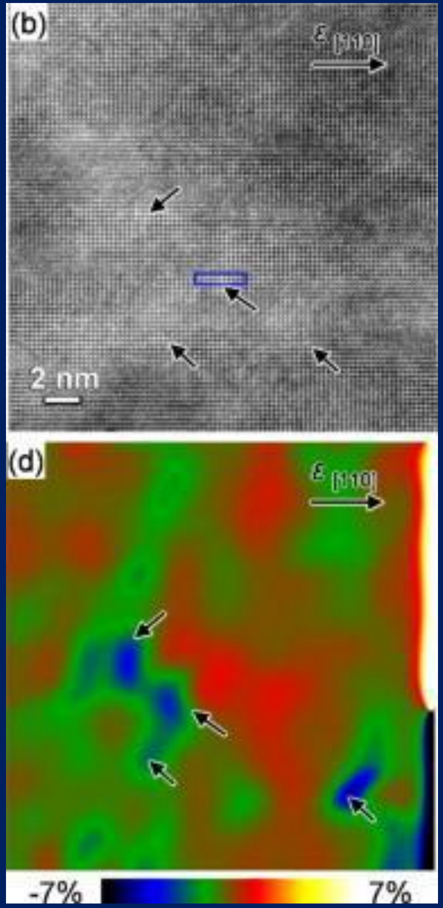
Insertion of a new atom with a different valence induces charge fluctuations :

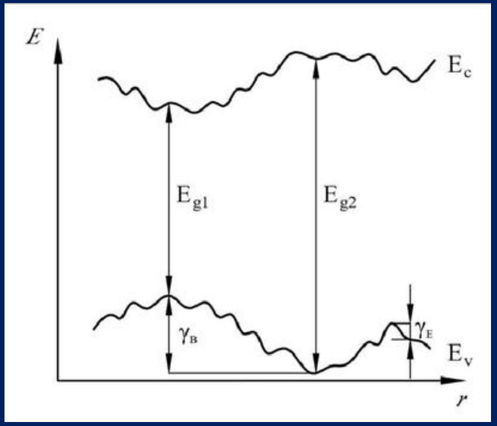
3



Local fluctuations of the potential

2





Fluctuations of the stoichiometry induces fluctuation of the band positions

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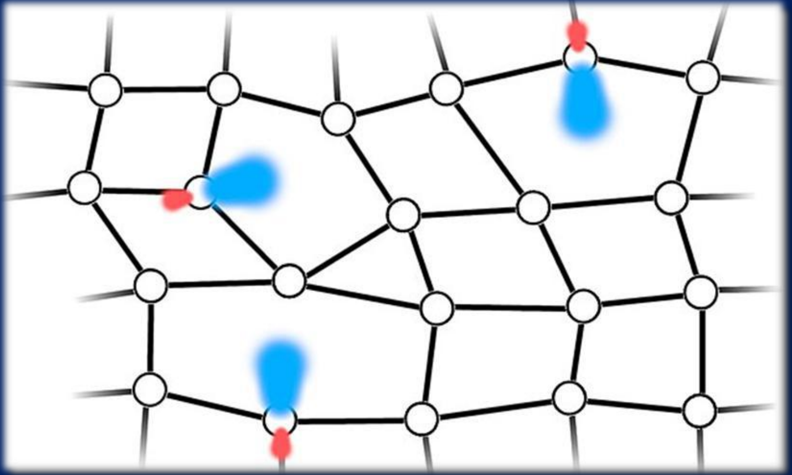
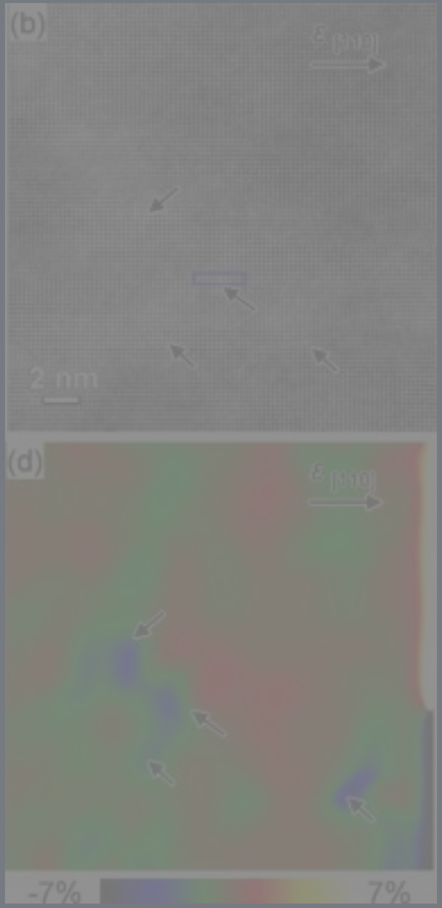
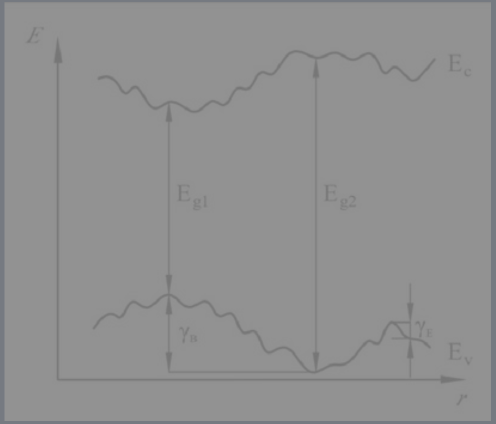


Local fluctuations of the potential

2





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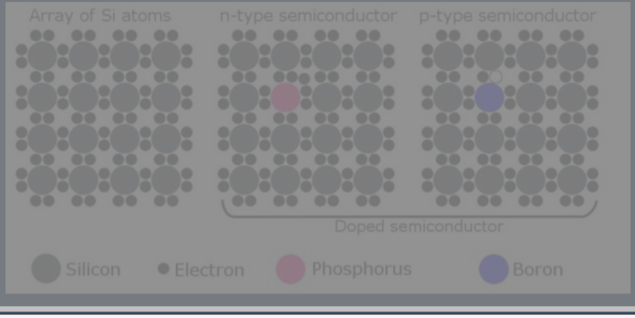
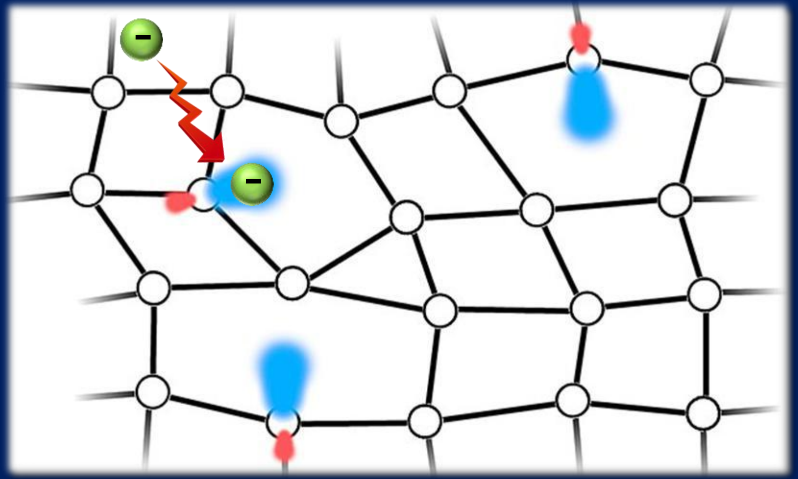
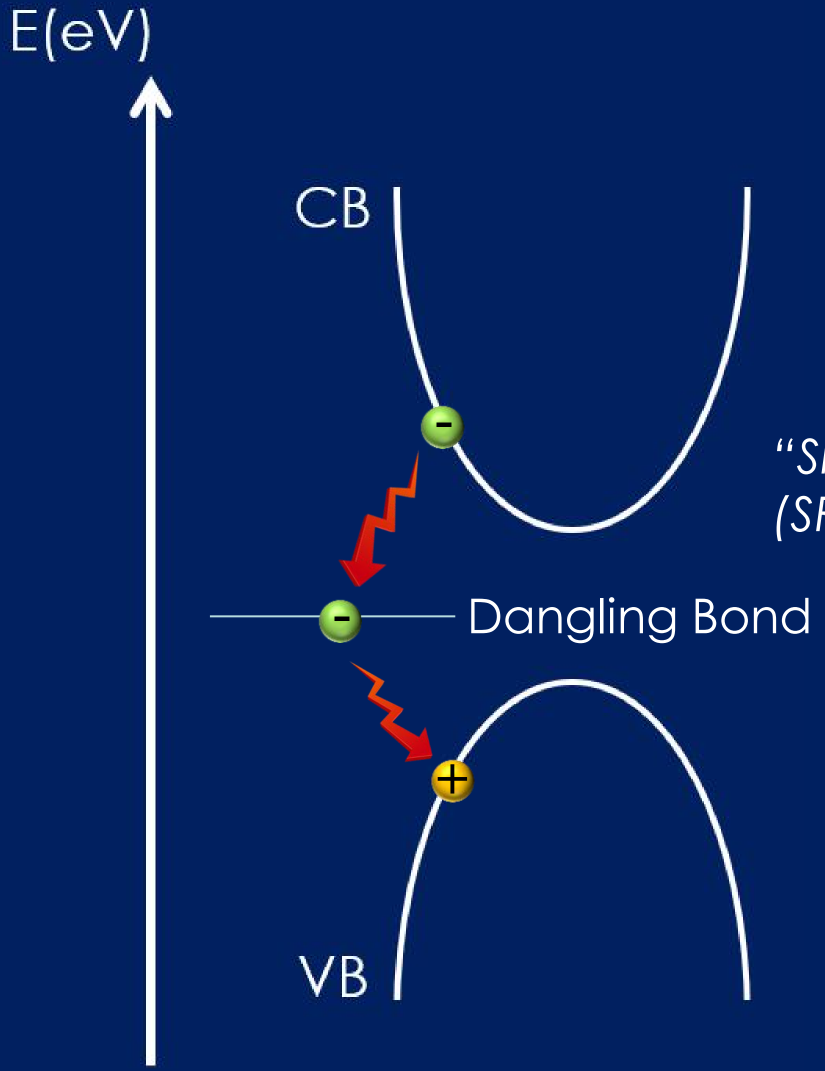


Dangling bonds and optical properties

Trapping of carriers in DBs



→Dangling bonds will capture carriers in the conduction band, which won't be available for light emission or carriers collection.

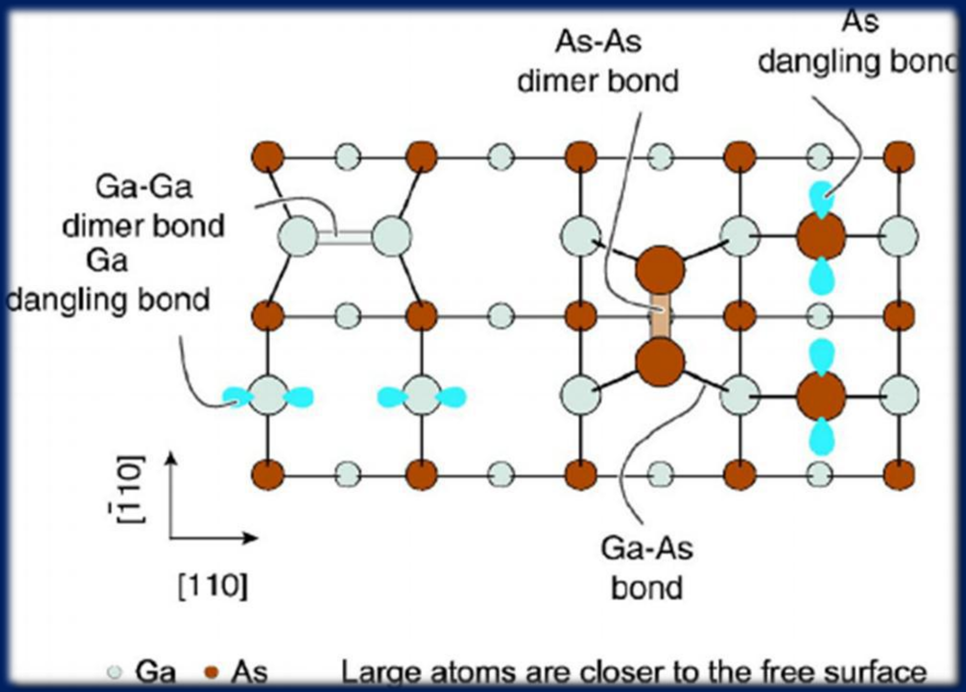


"Shockley–Read–Hall (SRH) recombination"

Dangling bonds in surfaces (2D)

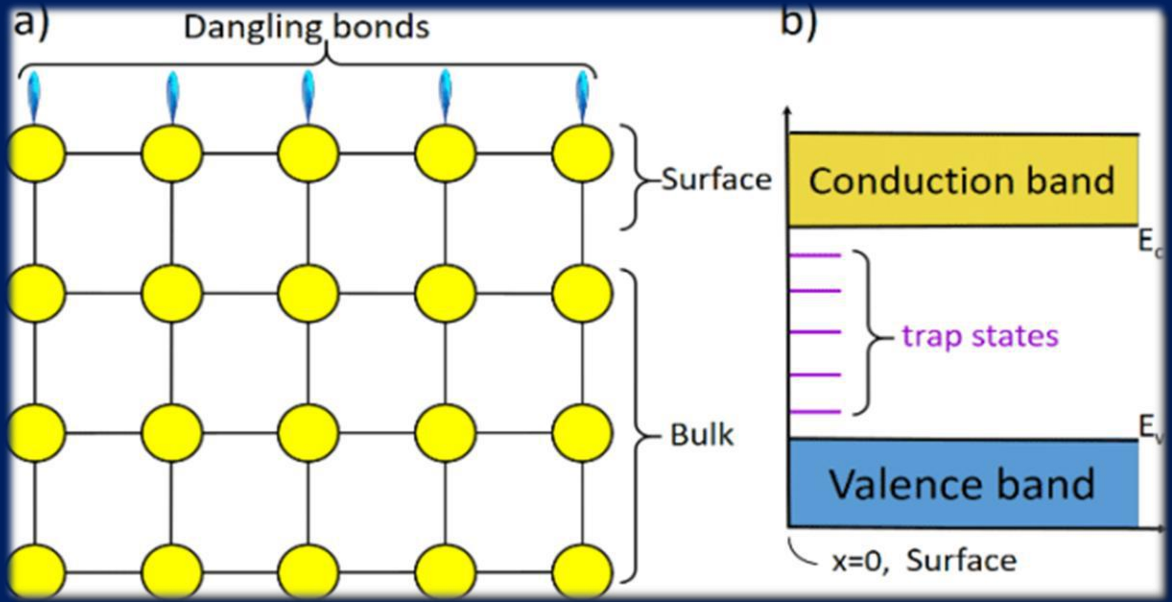
DBs at surfaces

- The free surface of a SC is usually full of Dangling Bonds !



Top view of the GaAs (001) surface.

"Surface states"



Mid band-gap states = surface states

- Decrease of optical efficiency, or carrier collection efficiency
- Surface passivation strategies (ex: Sulfur)

Dangling bonds in dislocations (1D & 2D)

Misfit dislocations & dangling bonds

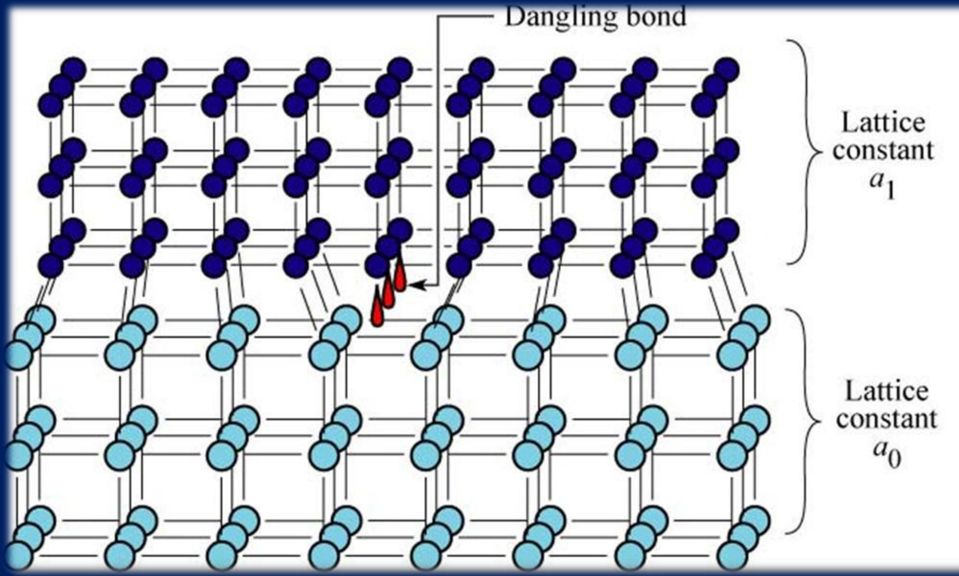
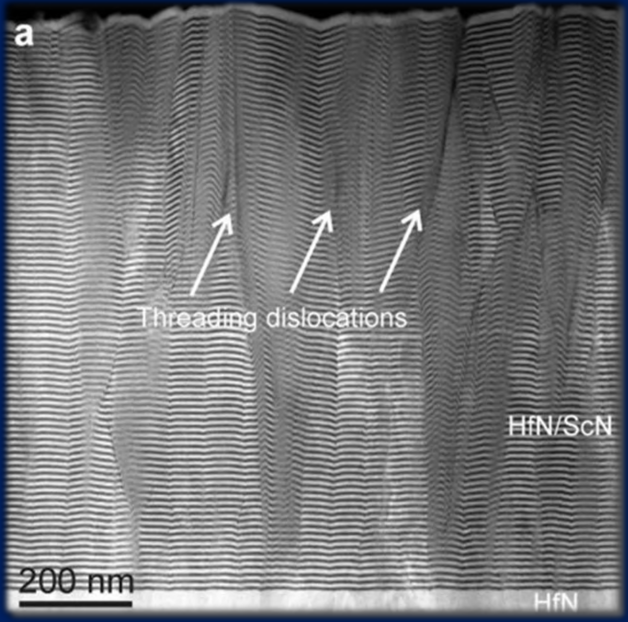


Fig. 7.12. Illustration of two crystals with mismatched lattice constant resulting in dislocations at or near the interface between the two semiconductors.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

The lattice mismatch between different layers will generally lead to misfit dislocations.

Propagation

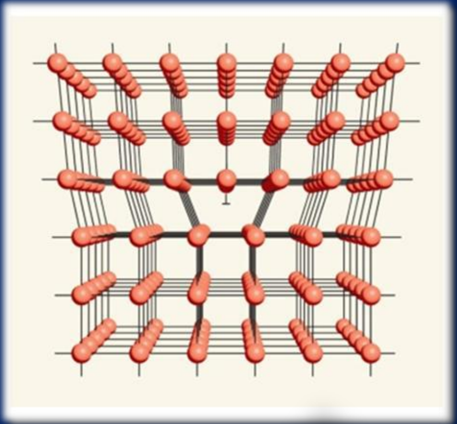


Dislocations density depends on the lattice mismatch, and are known to propagate through the entire sample.

Decrease of optical efficiency, or carrier collection efficiency (known as a *“device killer”*)

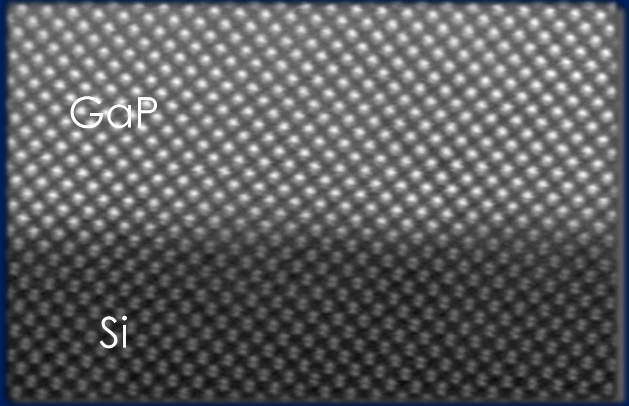
Dislocations management

Lattice mismatch

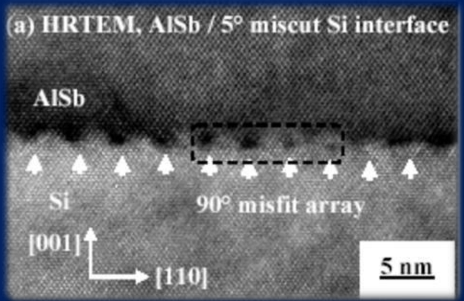


- Dislocations : a non-radiative defect that propagates

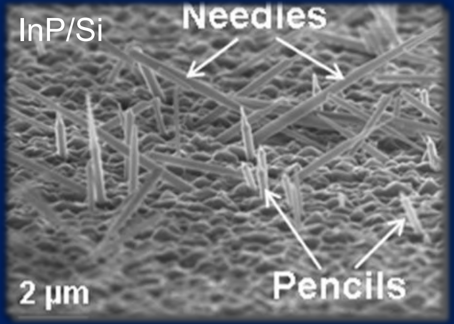
- Pseudomorphic approach



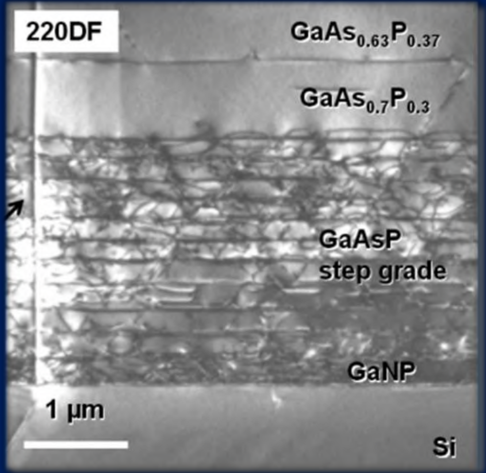
- Localized dislocations



- Nanowires



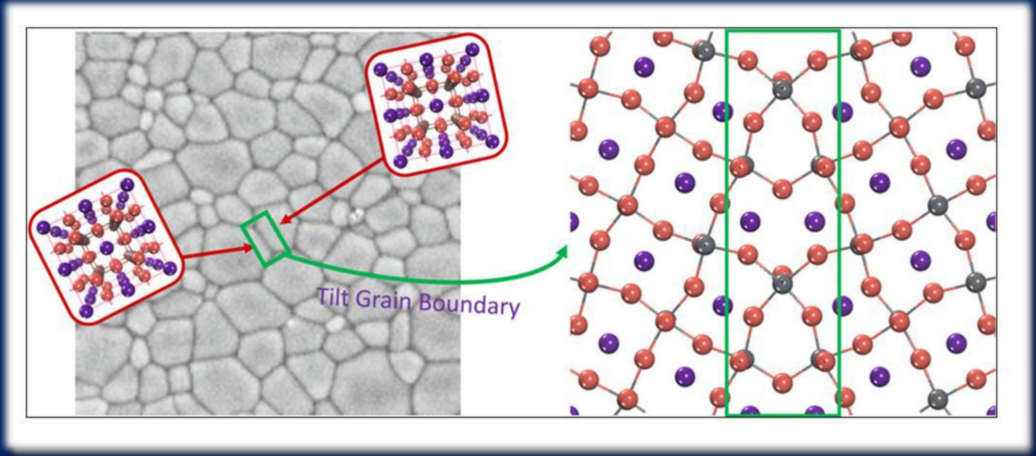
- Graded buffers



Dangling bonds in grain boundaries (2D)

Grain Boundaries : Epitaxy or not ?

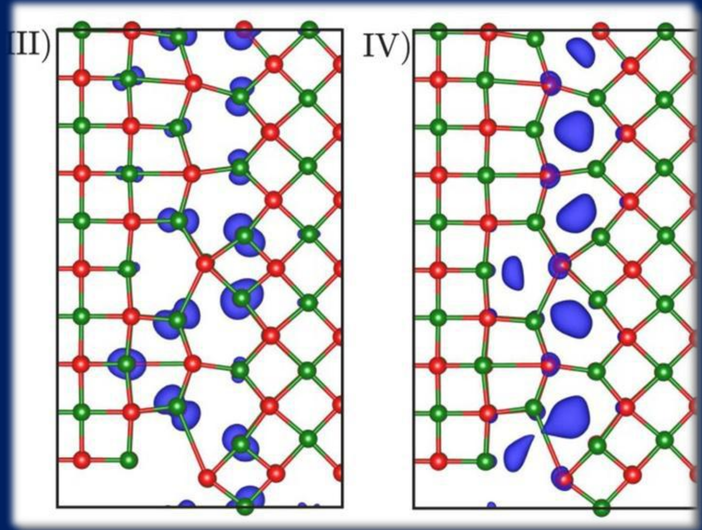
- Polycristalline materials, or bad quality epitaxial materials can present grain boundaries (originating from the coalescence)



Ex : Perovskites

Grain Boundaries and Dangling bonds

- Grain boundaries are usually full of DBs (trap states)



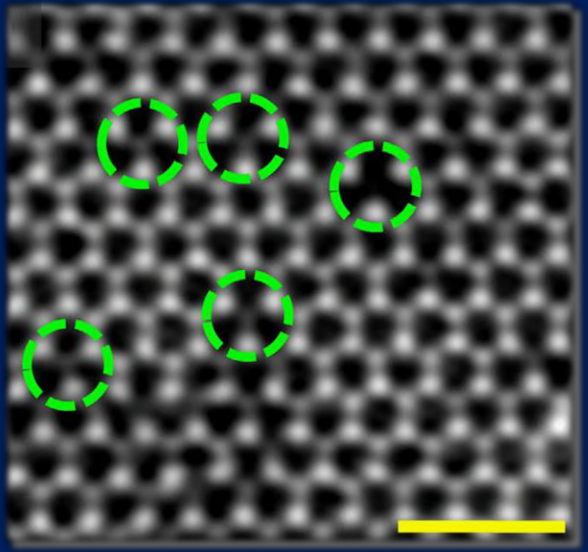
Ex: MgO

Also known as a *"device killer"*, *grain boundaries can be counter-passed e.g. in perovskites by potential fluctuations*

Dangling bonds in vacancies(0D)

Vacancies

- Vacancy = a missing atom in the crystal

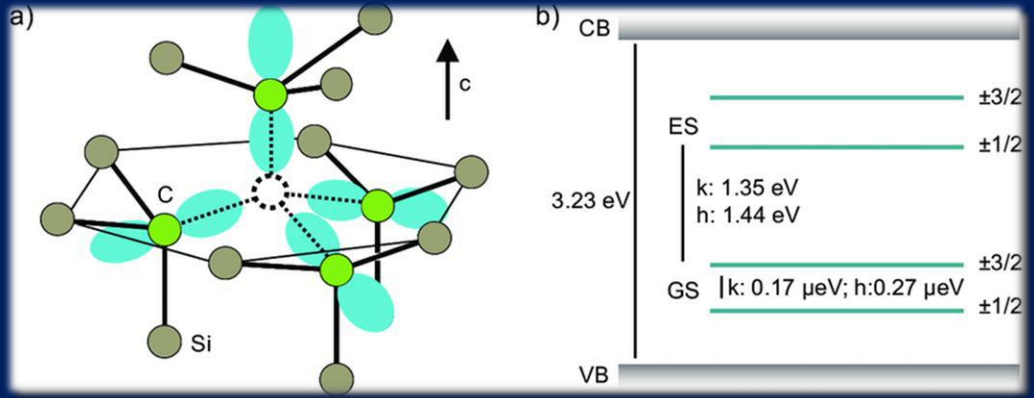


Ex : MoS$_2$

→detrimental for devices, but depends on the density.

Vacancy : is it really a defect ?

- Vacancy = a 0D nanostructure, with quanticized energy levels.



Ex : Si Vacancy in SiC

A real potential for quantum technologies ? (N-V centers)

Proposed classification of crystal defects

A dangling bond in a material is an unsatisfied valence on an immobilized atom

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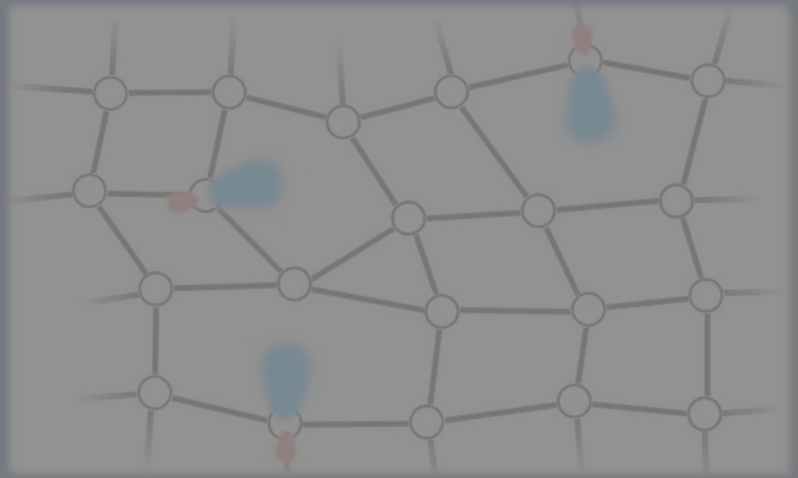

Insertion of a new atom with a different valence induces charge fluctuations :

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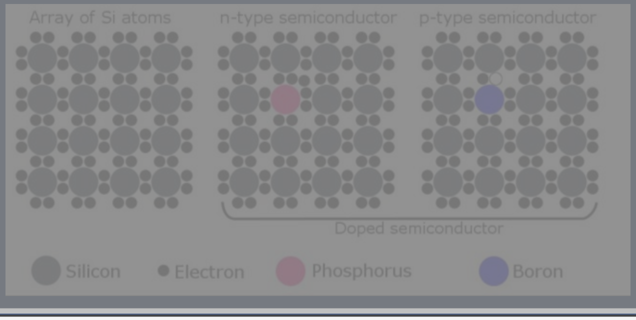
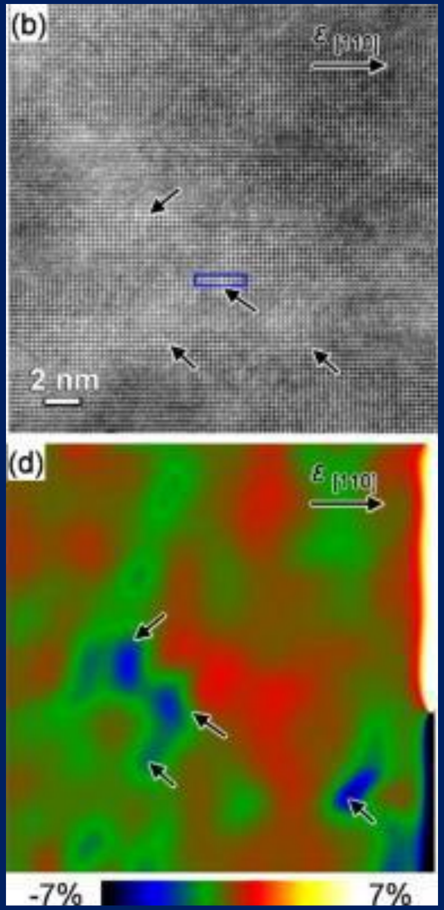
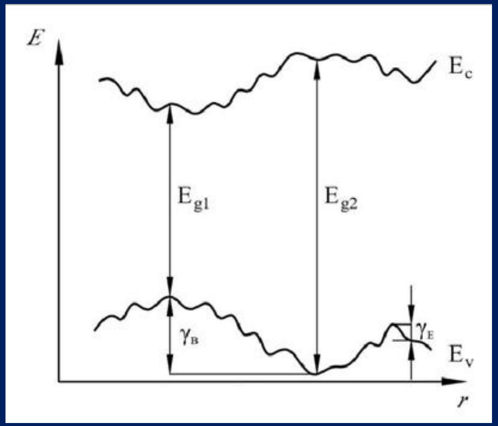


Local fluctuations of the potential

2

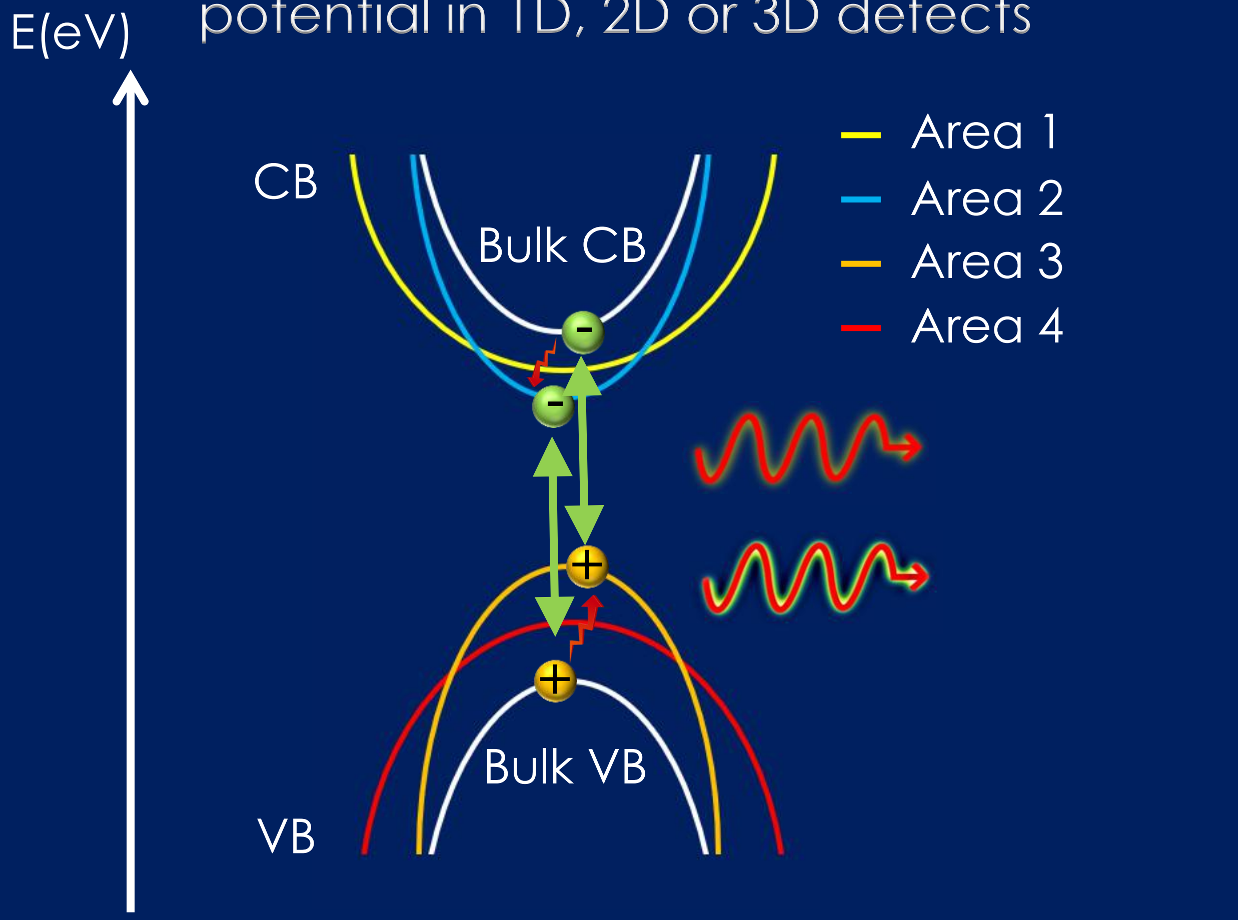




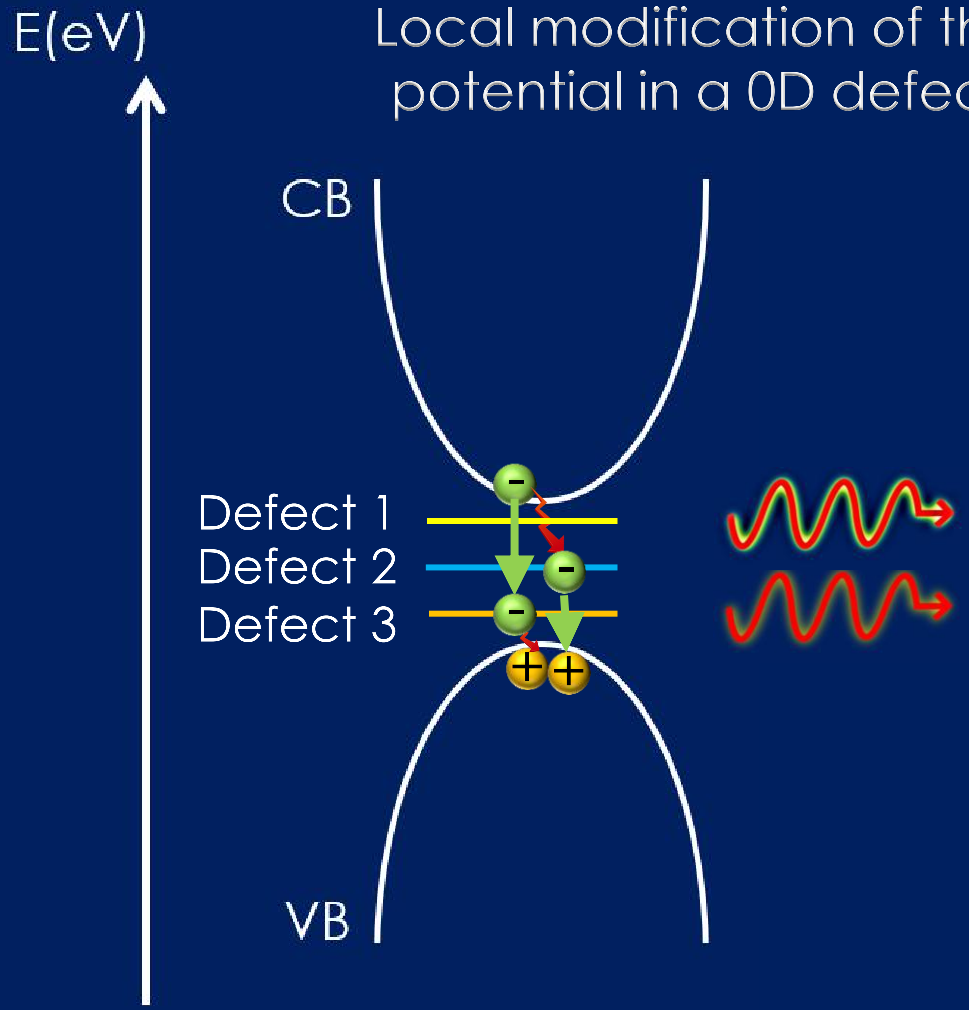
Fluctuations of the stoichiometry induces fluctuation of the band positions

Local fluctuations of the Potential

Local modification of the potential in 1D, 2D or 3D defects



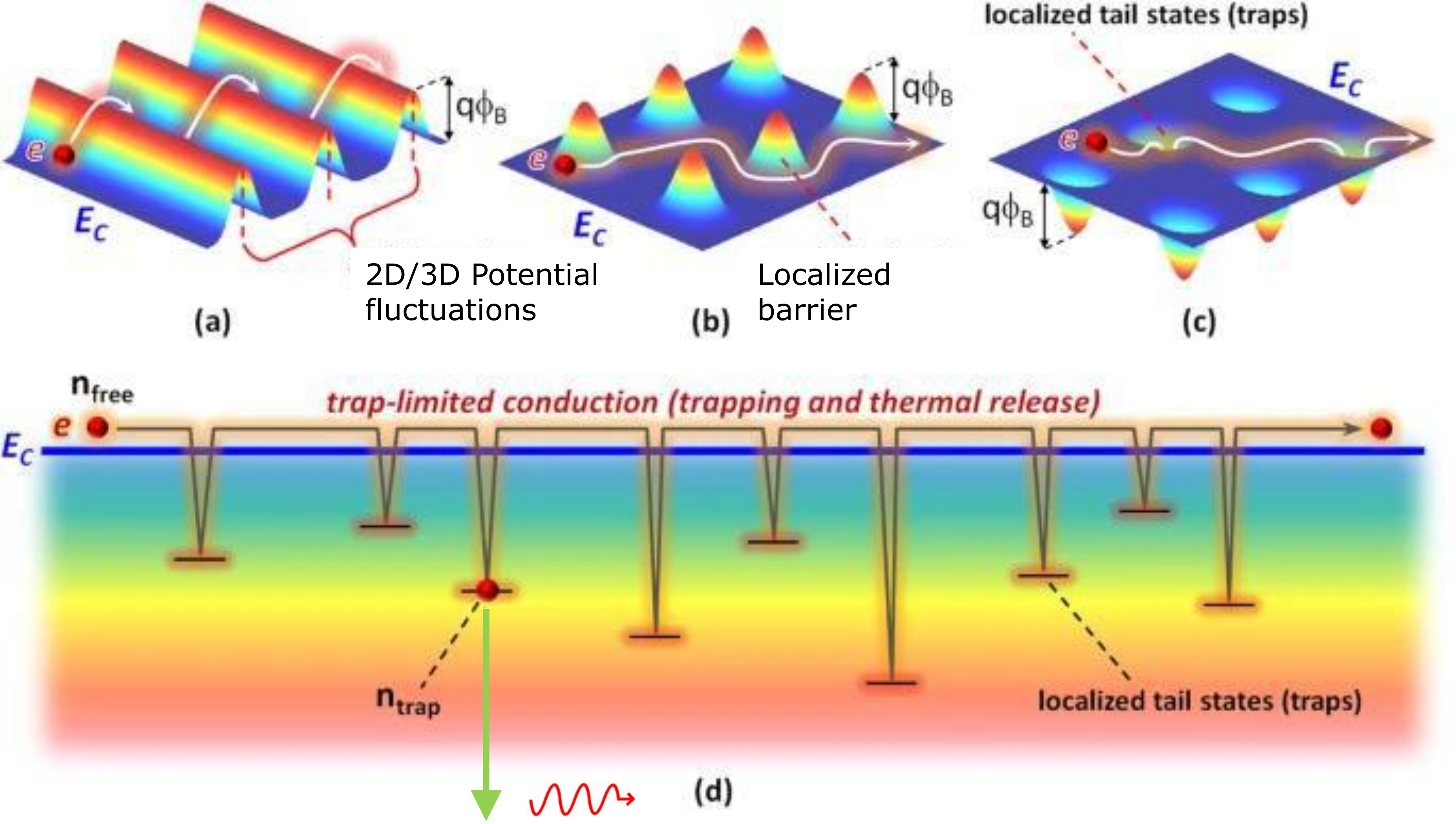
Local modification of the potential in a 0D defect



→Some defects will modify locally the bandstructure, leading to localization or barriers for transport.

Potential landscape seen by electrons

Potential landscape seen by an electron in a material with 0D, 1D, 2D or 3D defects

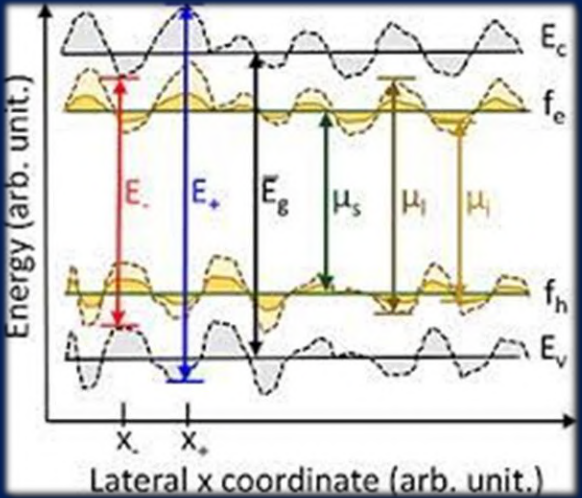


2D/3D Potential fluctuations

Localized barrier

Potential fluctuations due to disorder (3D)

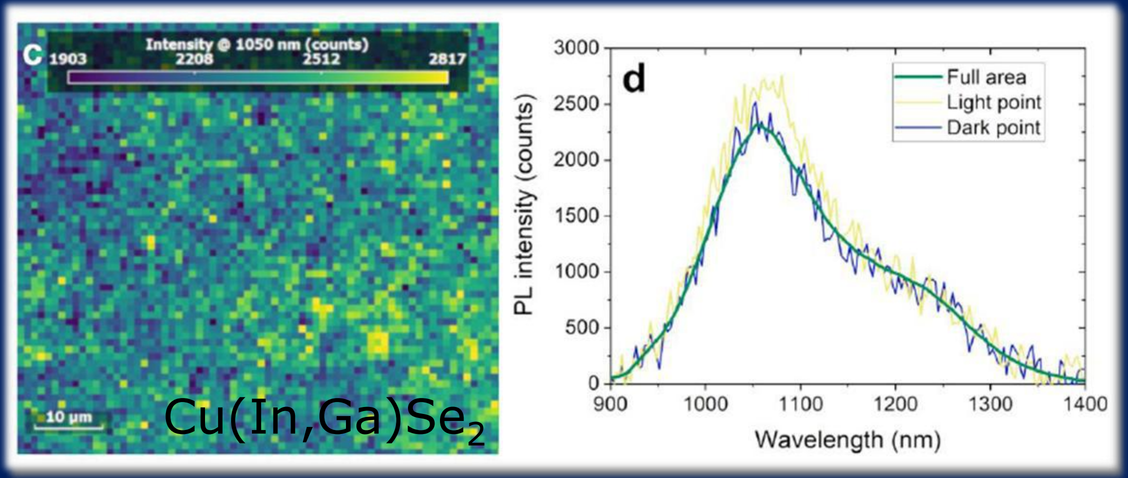
Entropic composition fluctuations of alloys: $A_xB_{(1-x)}$



→small variations of the composition during the growth can change the bandstructure

Consequences on optical properties

- PL mapping
- PL spectra

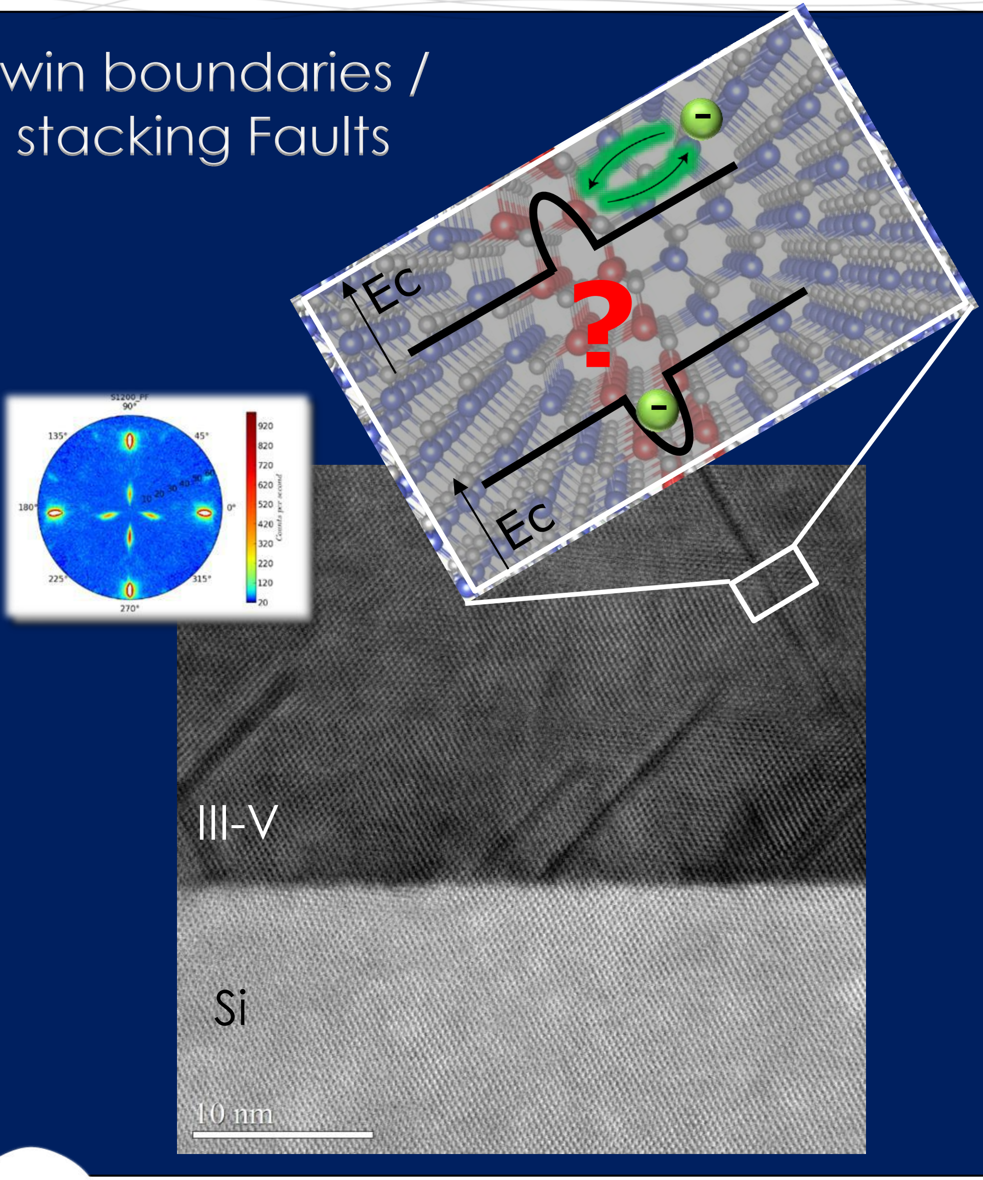


→Broadening of spectral width, inhomogeneity

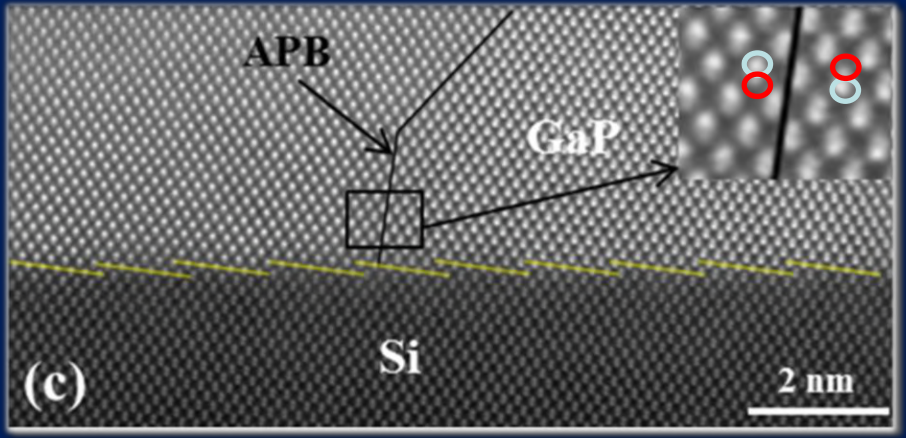
CB and VB will fluctuate over a scale typically >500 nm

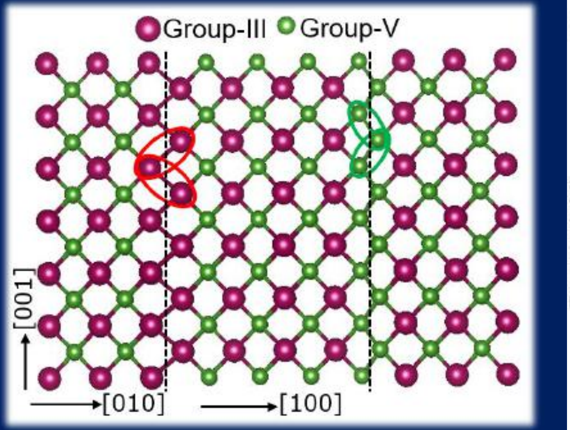
Potential fluctuations due to MT or APBs (2D)

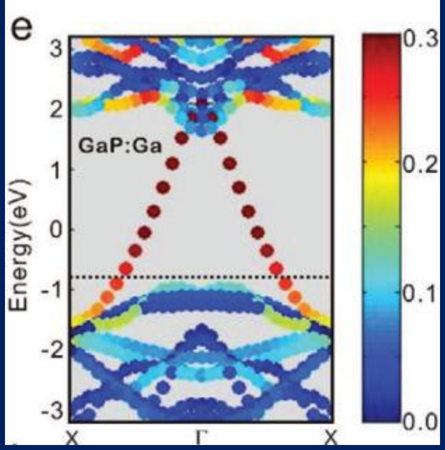
Twin boundaries / stacking Faults



Antiphase boundaries





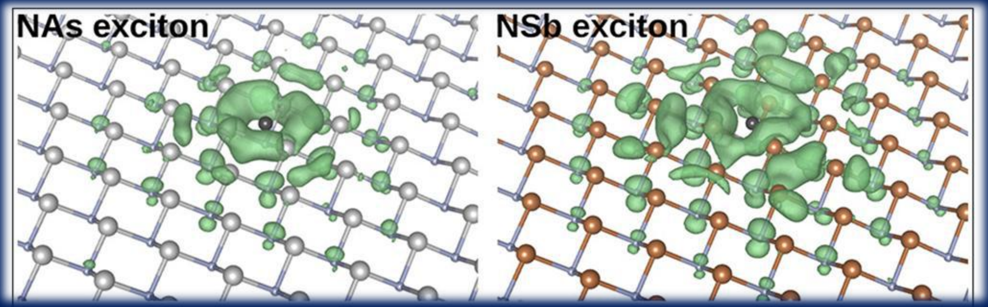


Strong modifications of the bandstructure : metallic inclusions ! (shortcuts)

Potential variations due to atomic fluctuations (0D)

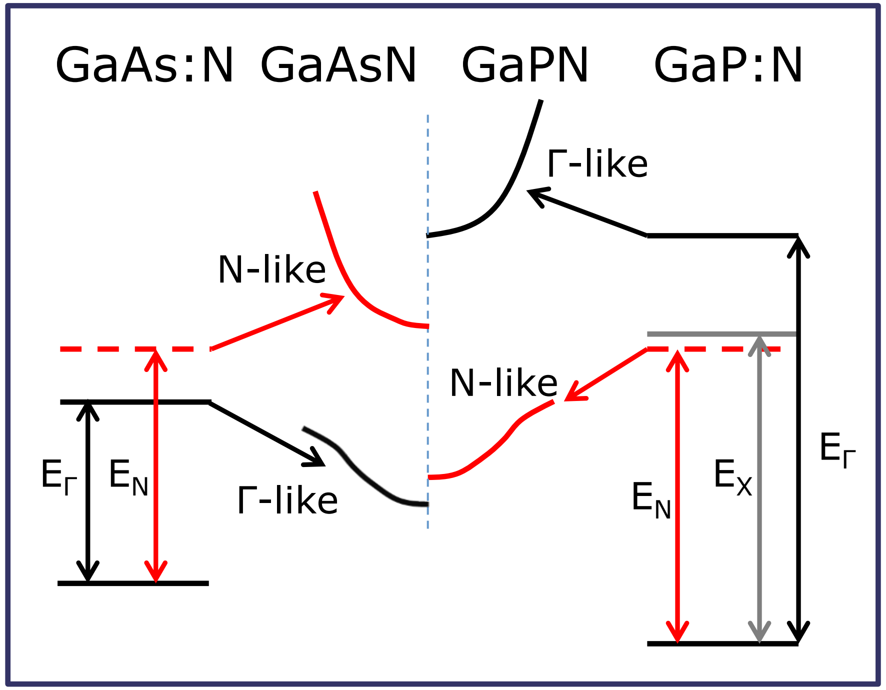
Diluted (metastable) alloys (x<5%)

- Incorporation of some atoms with very different valence configurations in a crystal (e.g. N or Bi in III-V semiconductors)



➡ Possible strong localization around the added atoms

Hybridization of Localized states



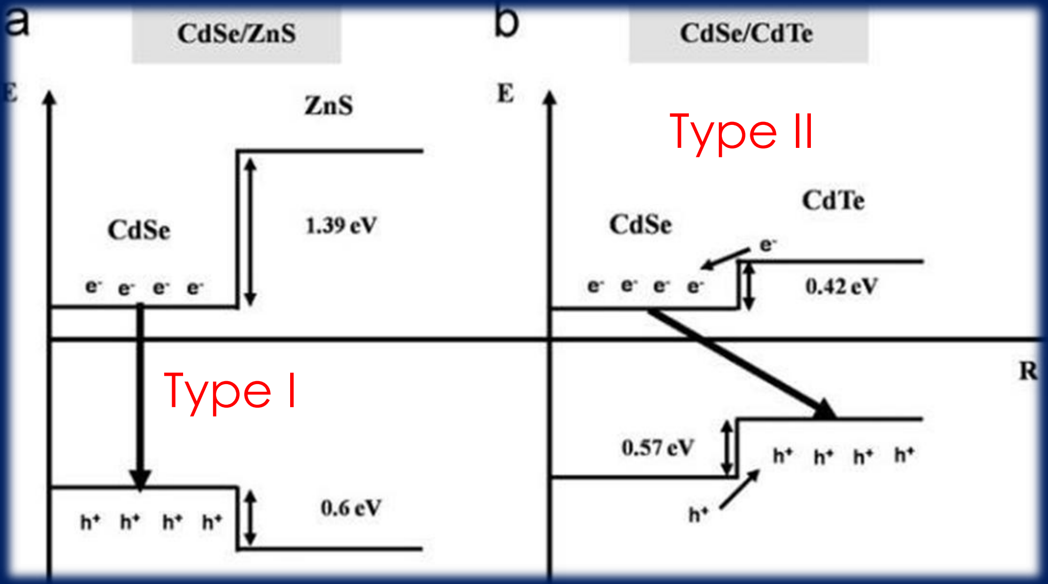
Ex : GaP(N) and GaAs(N)

➡ A unique nitrogen level interacting with the conduction band of the host material

Spatially separated electrons-holes pairs (2D-1D-0D)

Type I / type II band lineups

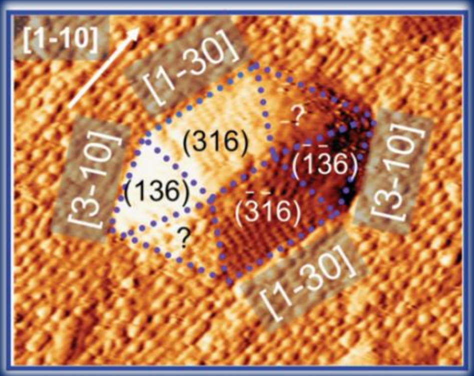
- Bandlineups between semiconductors are not always type I.

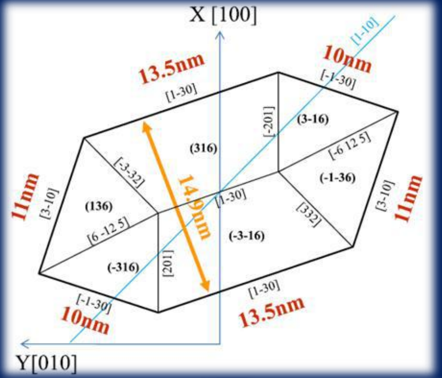


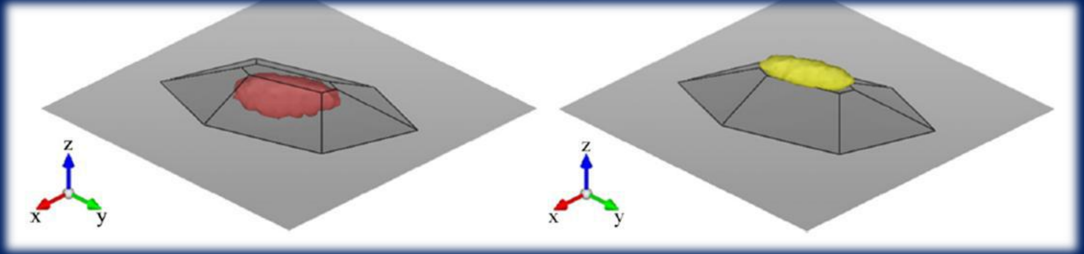
➡ The recombination of spatially separated e- and holes is less probable

Spatial overlap of wavefunctions

- Ex: (In,Ga)As/GaP QDs







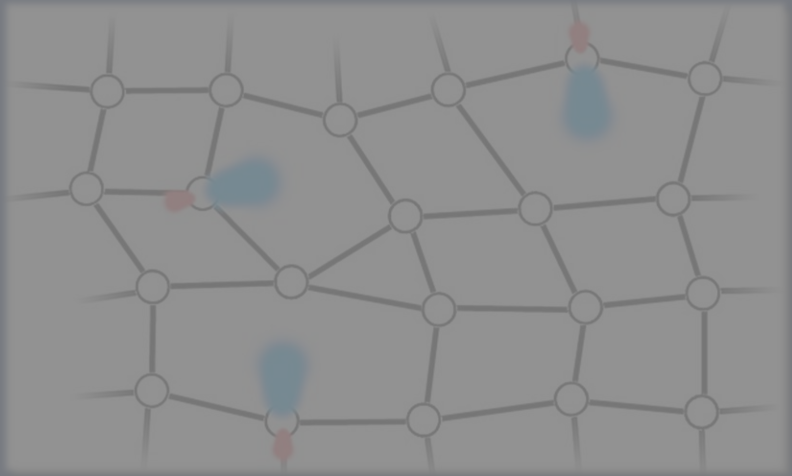
- Hole inside the QD
- Electron outside the QD

➡ Weak overlap→ weak luminescence

Proposed classification of crystal defects

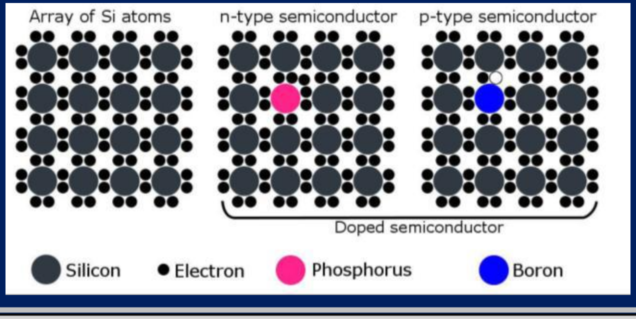
A dangling bond in a material is an unsatisfied valence on an immobilized atom

1



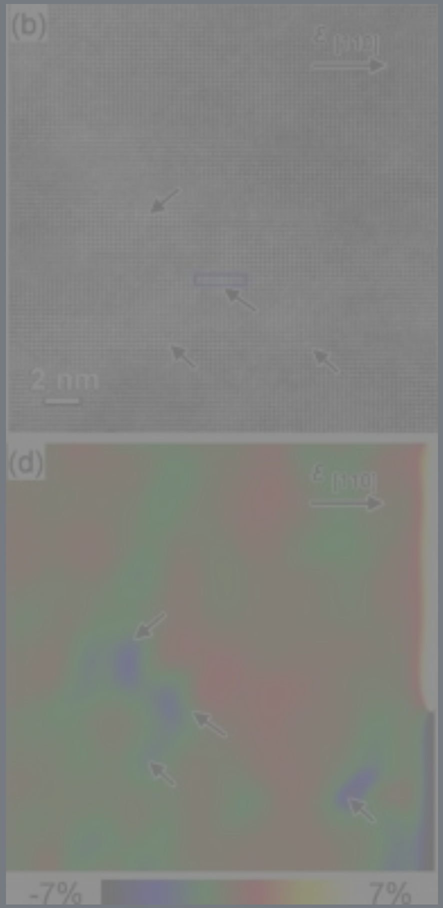
Insertion of a new atom with a different valence induces charge fluctuations :

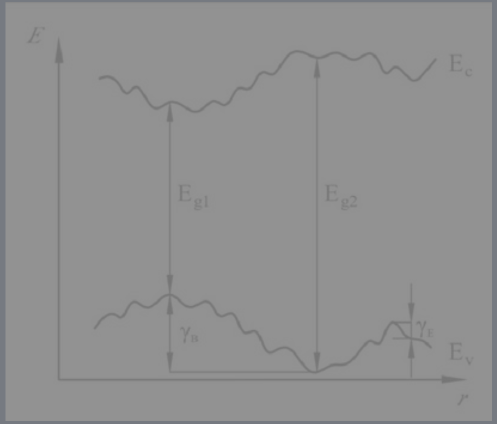
3



Local fluctuations of the potential

2

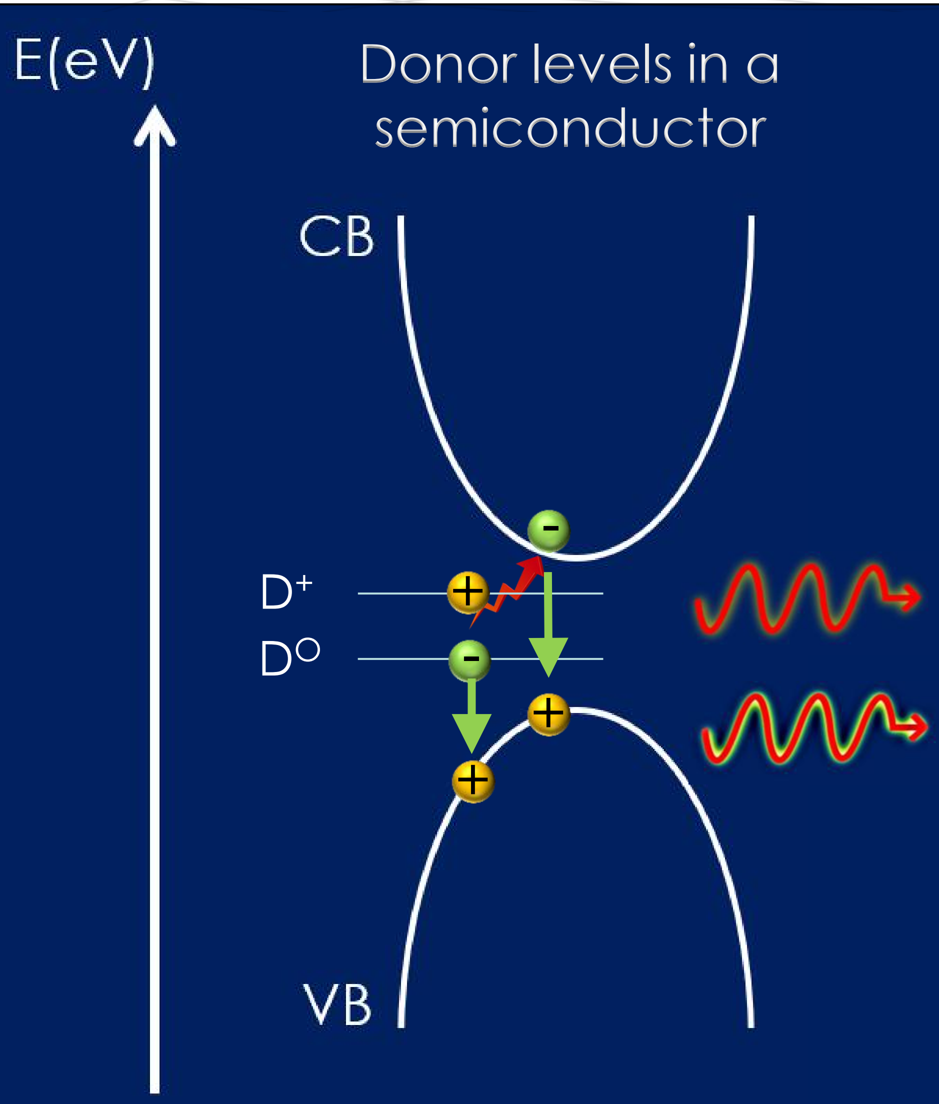




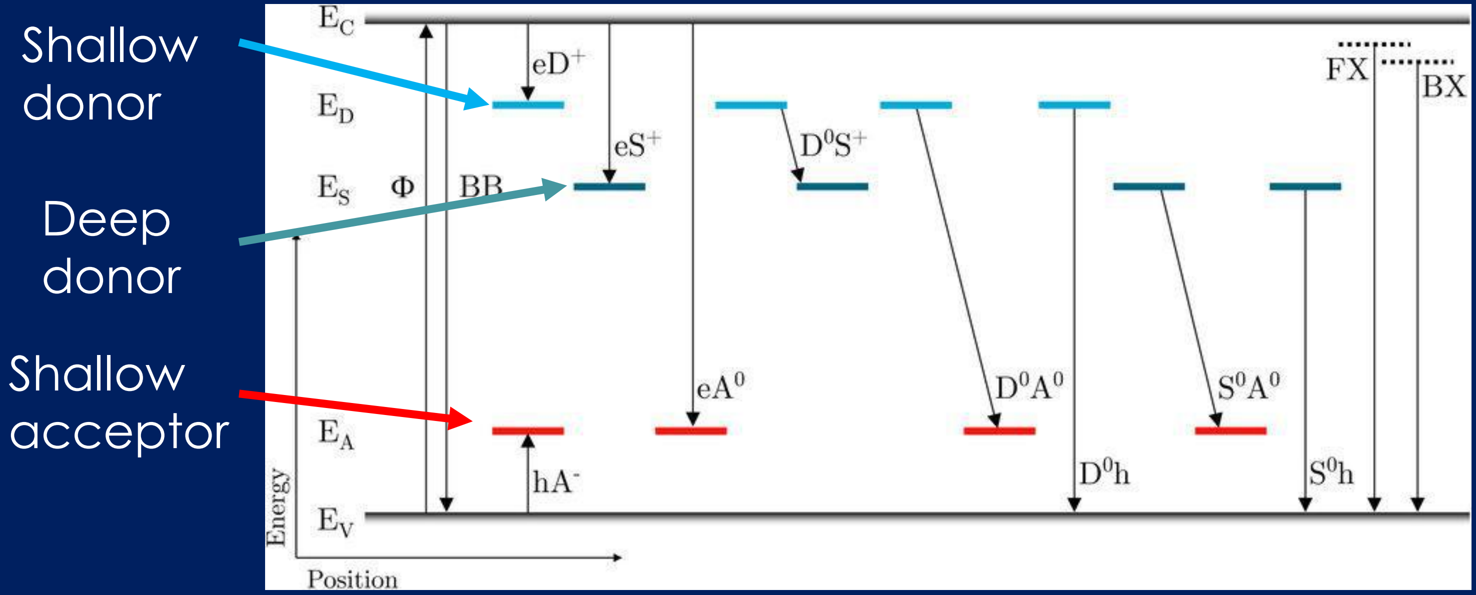
Fluctuations of the stoichiometry induces fluctuation of the band positions

Charge variations due to donors/acceptors (dopants 0D)

Donor levels in a semiconductor



The acceptors/donors radiative properties


Shallow donor

Deep donor

Shallow acceptor

Many optical transitions enabled by the presence of donors or acceptors in a semiconductor

Intermediate conclusion

Crystal defects in semiconductors

1 Crystal defects with Dangling Bonds

Ex : Surfaces, Dislocations, grain boundaries, vacancies

→Non-radiative recombination defects (loss of carriers)

2 Potential fluctuations in the Crystal

Ex : Alloy disorder, MT, APBs, diluted alloys, type II SCs.

→Modification of transport properties and of the bandgap

3 Charge fluctuations in the Crystal

Ex : Doping, impurities, donors, Acceptors.

→Modification of transport properties and of the bandgap

In any cases, a strong impact on photoelectric properties of devices (volumic density and dimensionality of defects matters !)

Outline

I-Bandstructure of semiconductors, crystal defects and optical processes

-Bandstructures and semiconductors

-Crystal defects and their impact on optoelectronic properties

II-Characterizing light emission properties

-Photoluminescence

-Electro- & Cathodo-luminescence

III-Characterizing light absorption properties

-Absorbance measurements

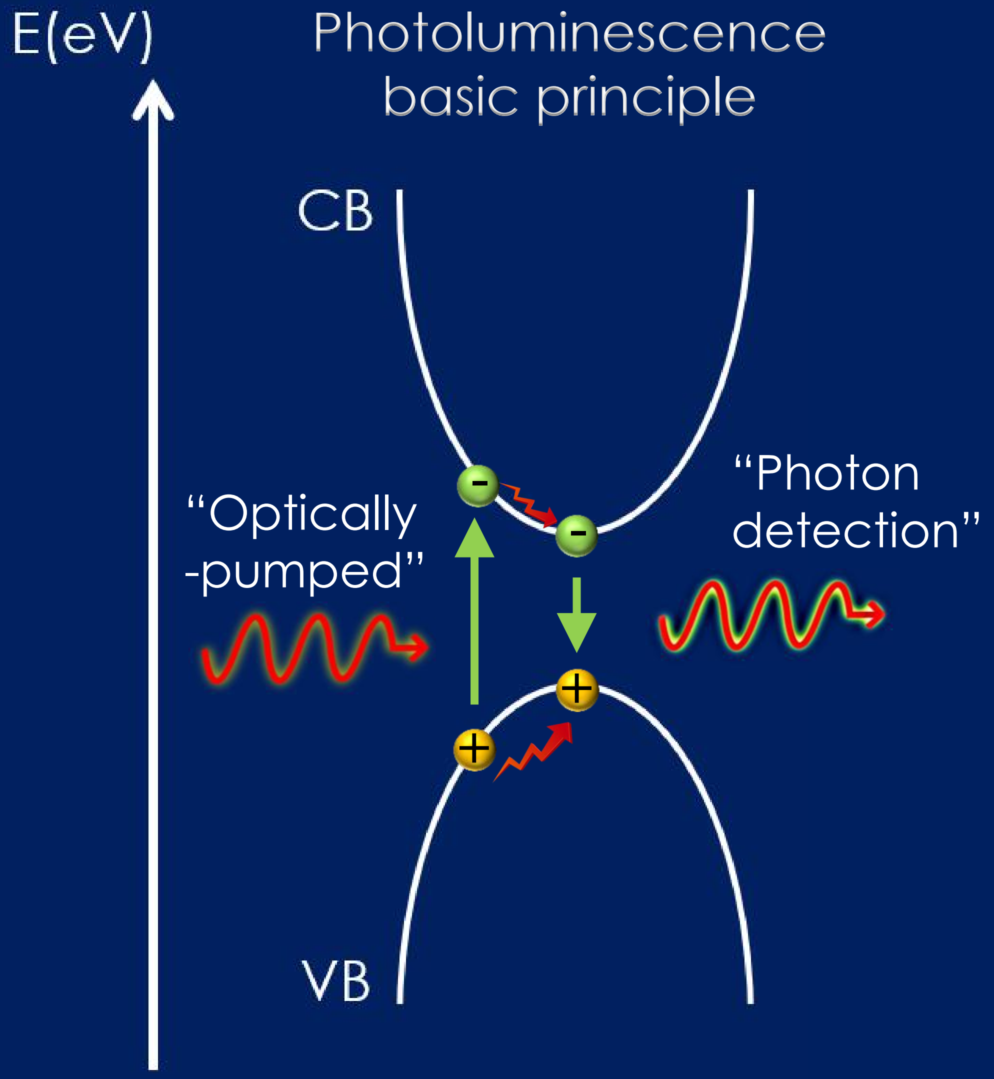
-Ellipsometry & Photo-current

IV-Toward single photons sources

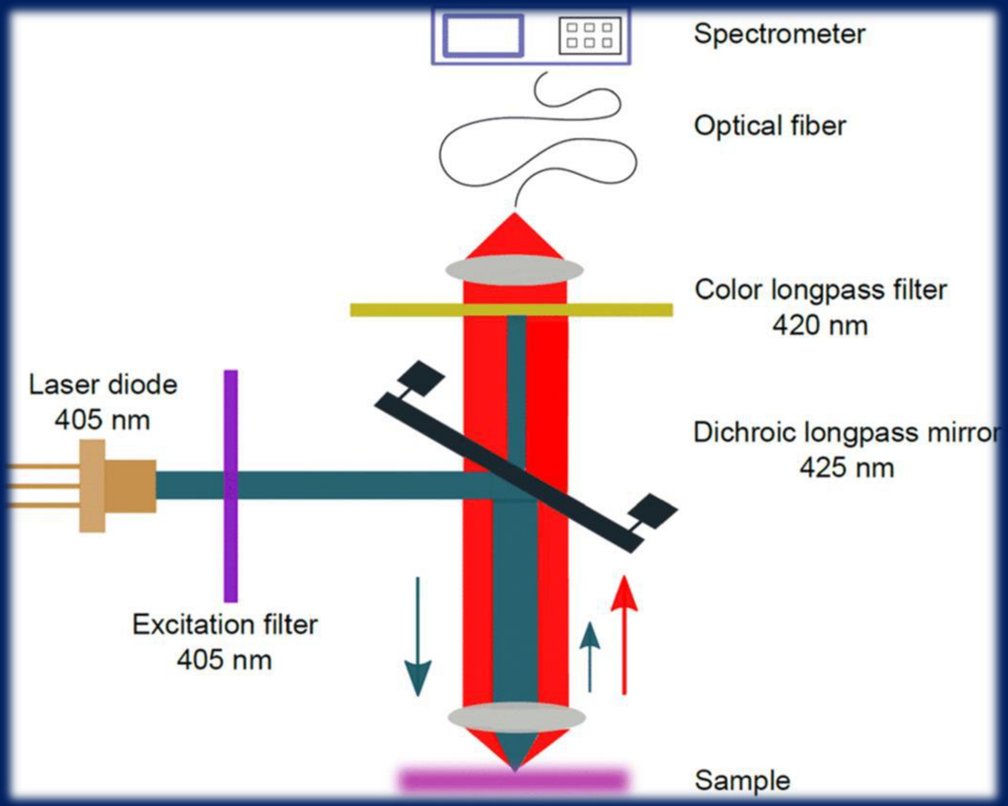
-micro-photoluminescence, g(2)

PL basic principle and setup

Photoluminescence basic principle



Photoluminescence basic setup



Typical RT PL setup, with a laser pumping at 405 nm

PL Experimental setups

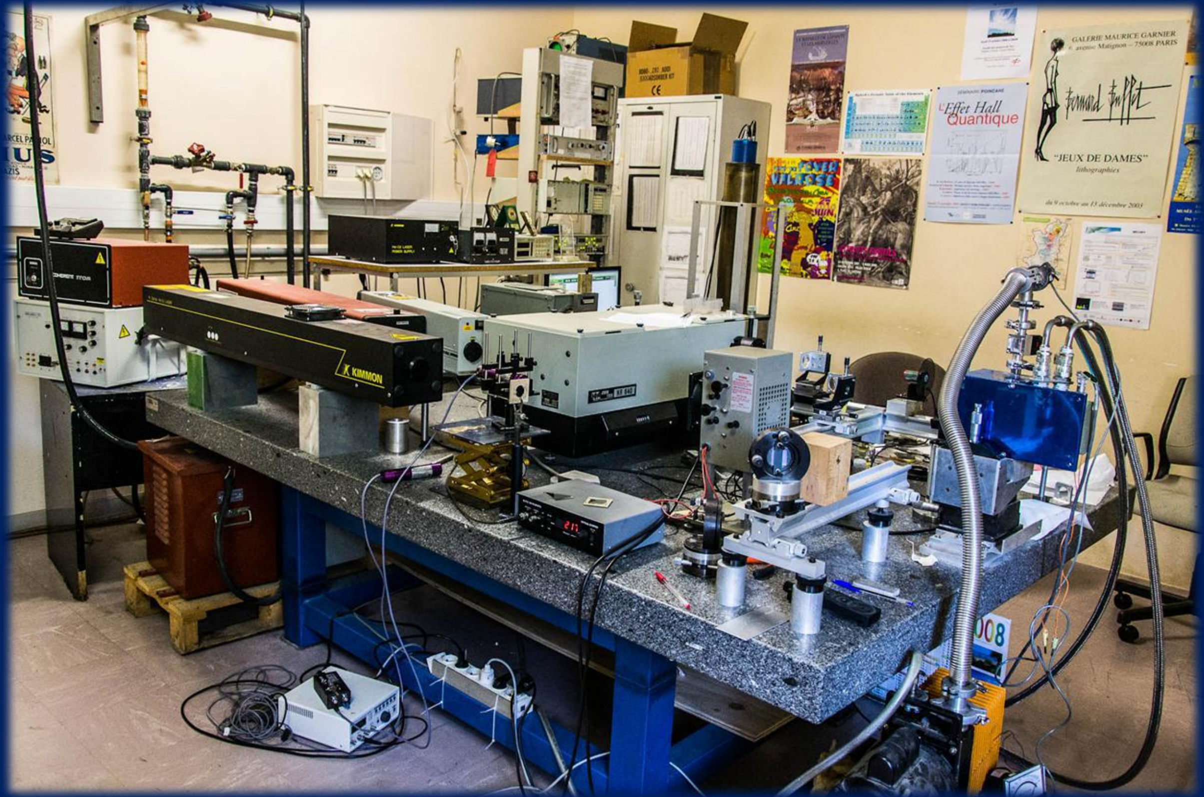
Starting first PL experiments, …

Excitation Laser

CCD spectrometer

Few optical components

…Few years later…



Power, temperature, time-resolved, µ-PL, mapping …

PL : Is it really simple ?

The PL processes

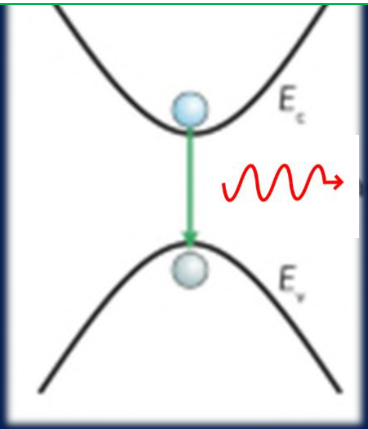
- Understanding optical properties of materials = understanding time constants
- Probability of a process to happen :

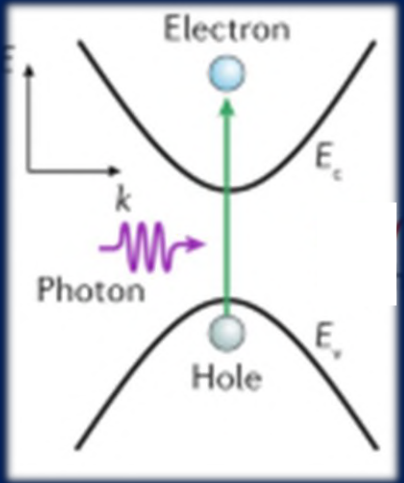
$$\tau \Longleftrightarrow k$$

time constant (s) Process rate (s^{-1})

Radiative recombination

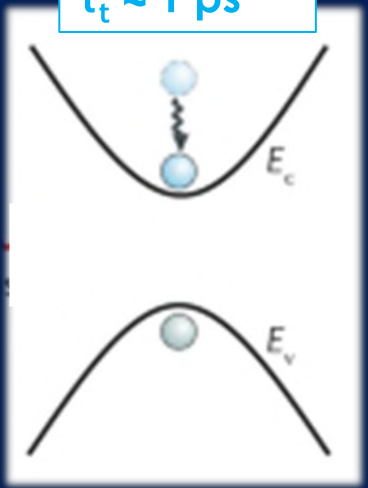
$0,1\ ns < \tau_r < 1\ ms$





Absorption

$\tau_t \approx 1\ ps$

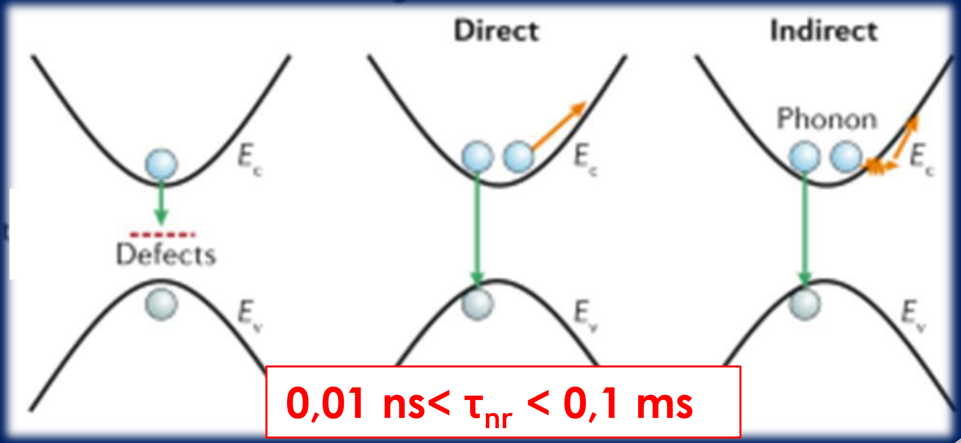


Thermalization

Non-radiative recombination

SRH

Auger

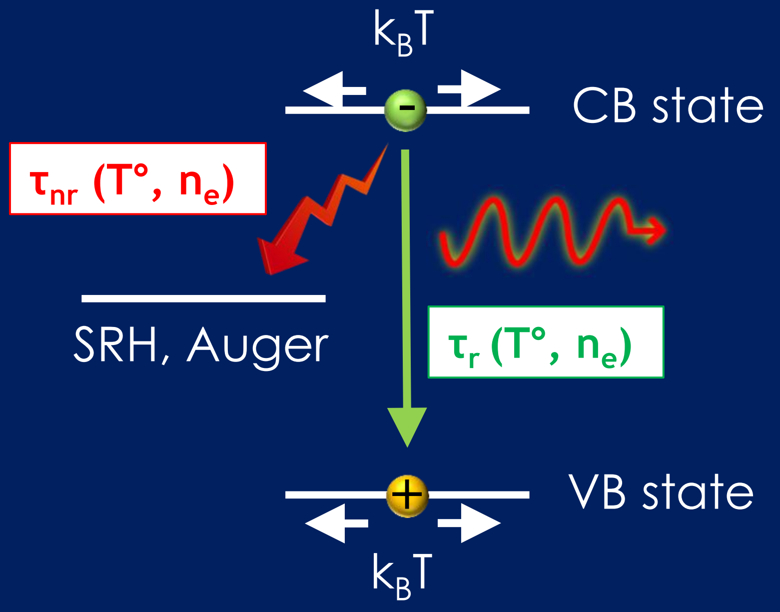


$0,01\ ns < \tau_{nr} < 0,1\ ms$

$\tau_t << \tau_r\ ,\ \tau_{nr}$

The general picture

- Most of the PL processes can be understood with the following simplified picture :



k_BT

CB state

τ_{nr} (T°, n_e)

SRH, Auger

τ_r (T°, n_e)

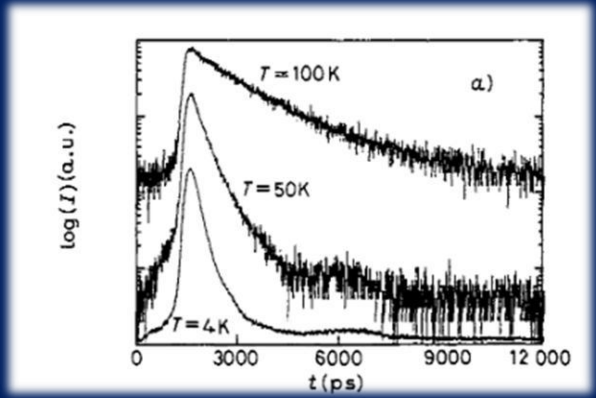
VB state

k_BT

- Global Lifetime of the luminescence:

$$\tau = \frac{1}{k_r + kn_r}$$

Measured in time-resolved PL

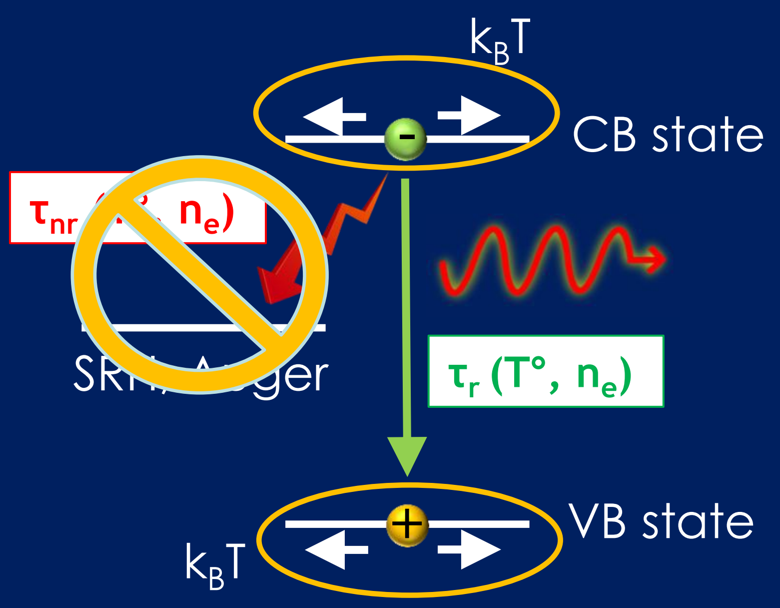


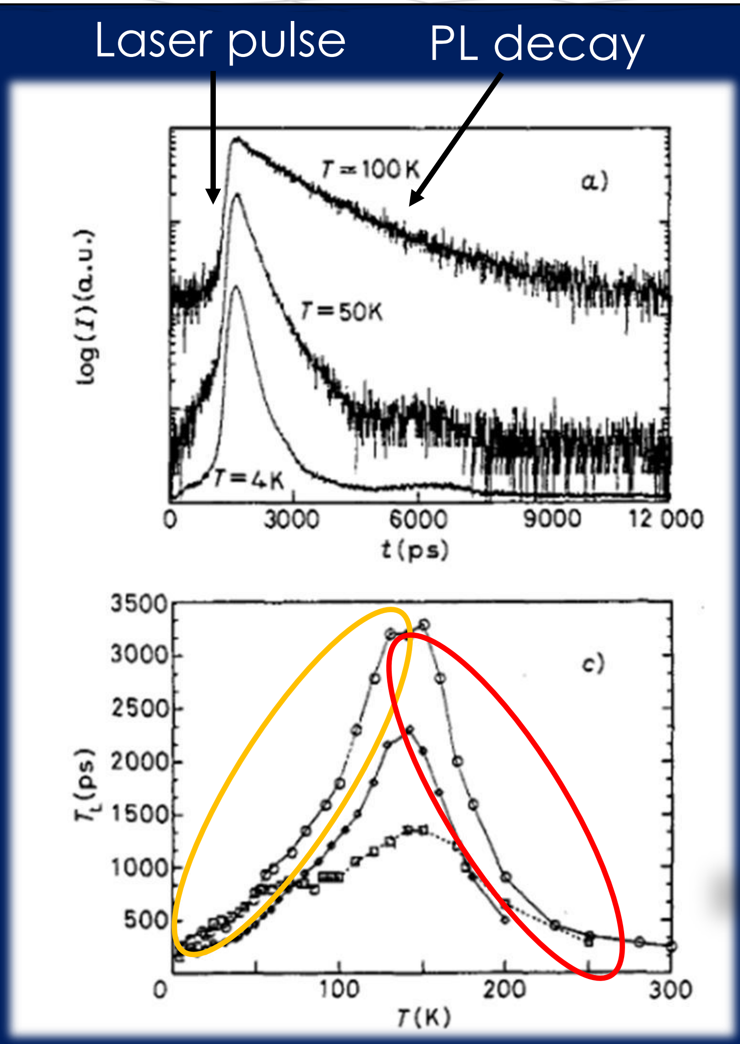
- Quantum yield (∝ PL intensity):

$$Q = \frac{k_r}{k_r + kn_r}$$

Influence of the temperature

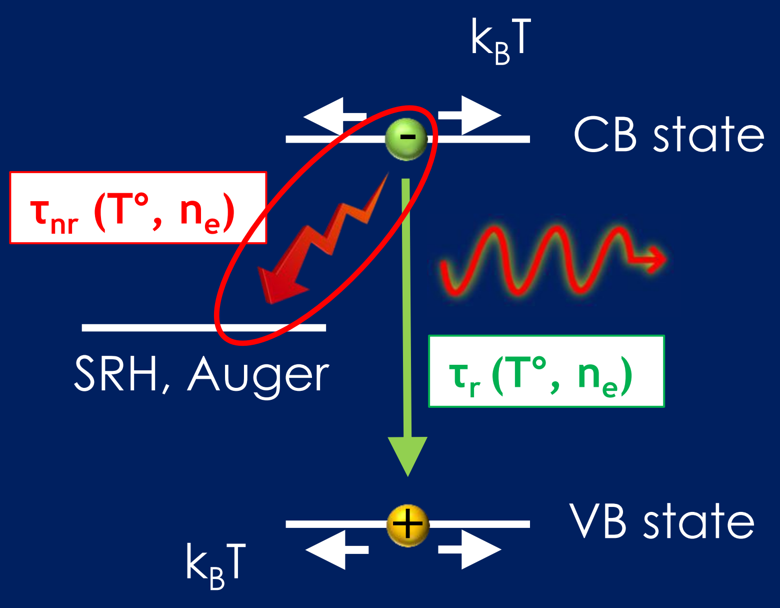
Low T (<100 K)





Global T-dependent PL lifetimes (III-V SC QW)

high T (>100 K)



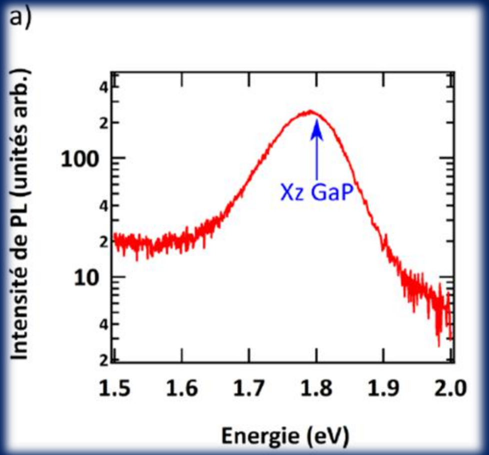
- Low T measurements are a signature of pure radiative properties of the sample (w/o defects)
- High T and RT measurements depend on NR and R competition
- RT PL measurements are not sufficient to conclude on crystal defects or intrinsic efficiency

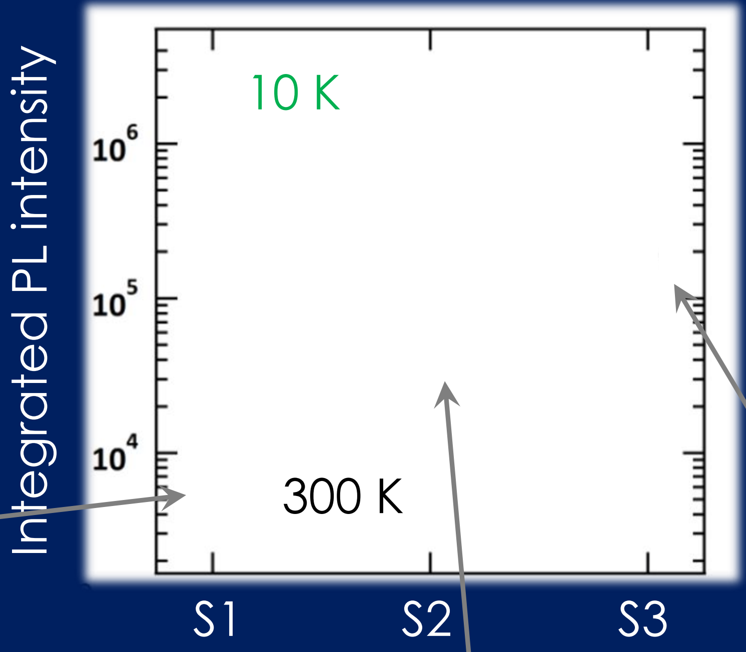
Simple Illustration with QDs PL

Ex: 3 samples with QDs grown on GaP with different growth conditions, analyzed in the same PL conditions

Sample S1

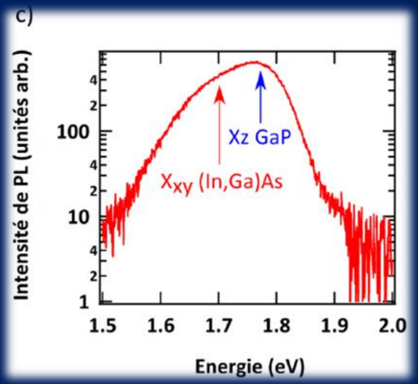
→Low PL intensity at RT





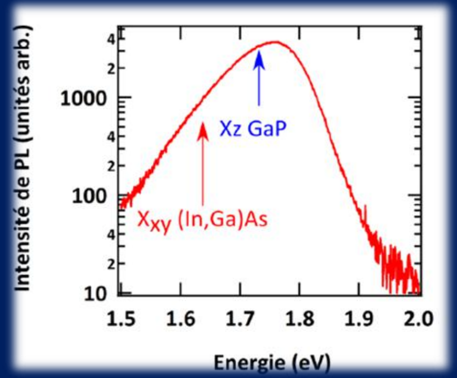
Sample S2

→Intermediate PL intensity at RT



Sample S3

→High PL intensity at RT

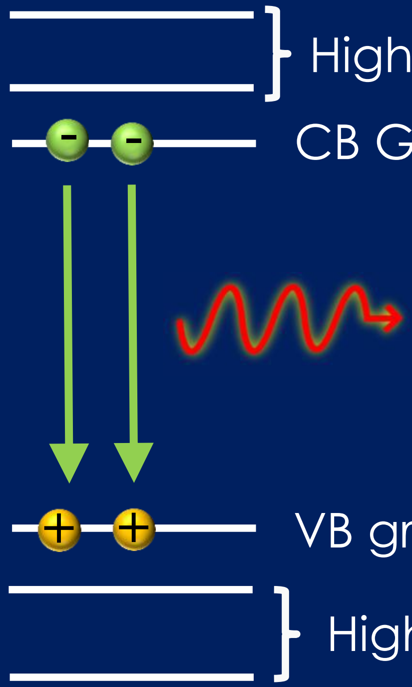


CRYSTAL DEFECTS ?

- The RT alone can lead to erroneous conclusion !
- The low-T PL enables to exclude impact of crystal defects

Influence of the incident power

Low Excitation density D



Higher energy states

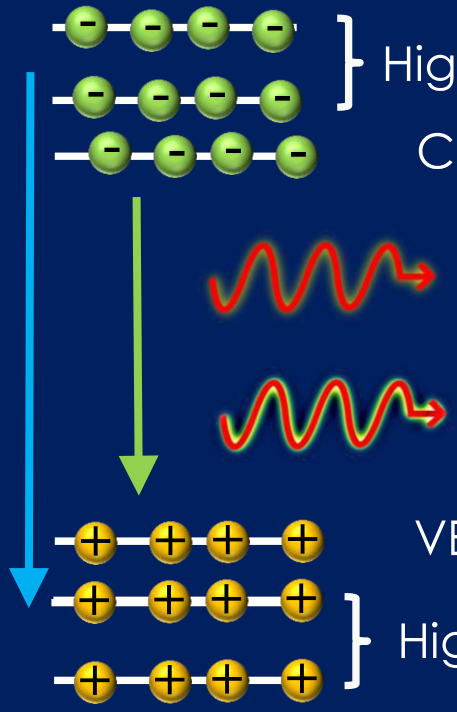
CB Ground state

VB ground state

Higher energy states

Information on the ground state of the system

high Excitation density D



Higher energy states

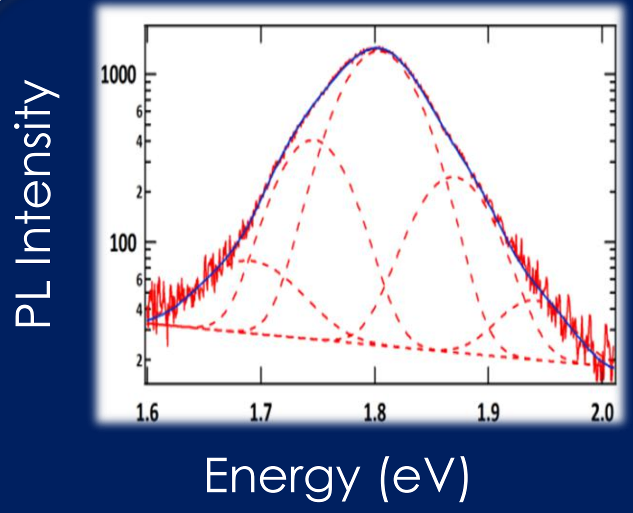
CB state

VB state

Higher energy states

Information on higher energy states in the system

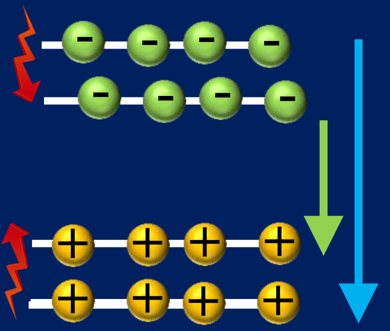
Illustration

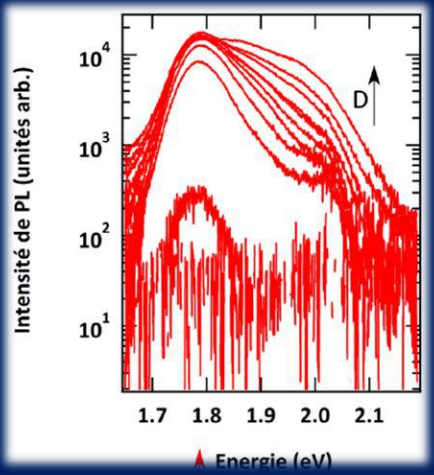


PL peak composed of multiple transitions ?

Excited states of the same object ?

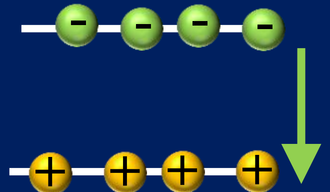
-Quantum confined systems ?

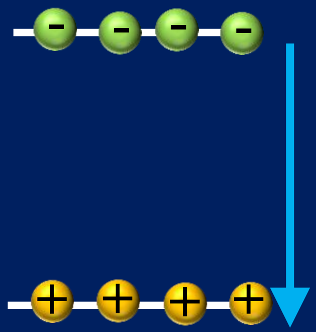


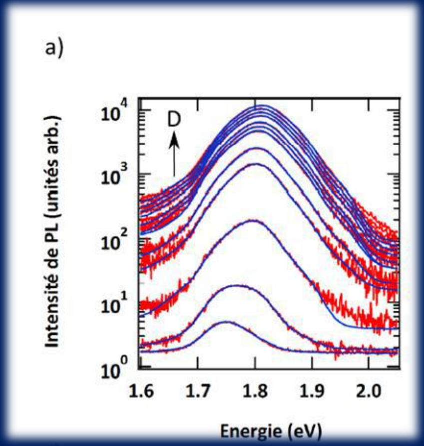


Independent Higher energy states ?

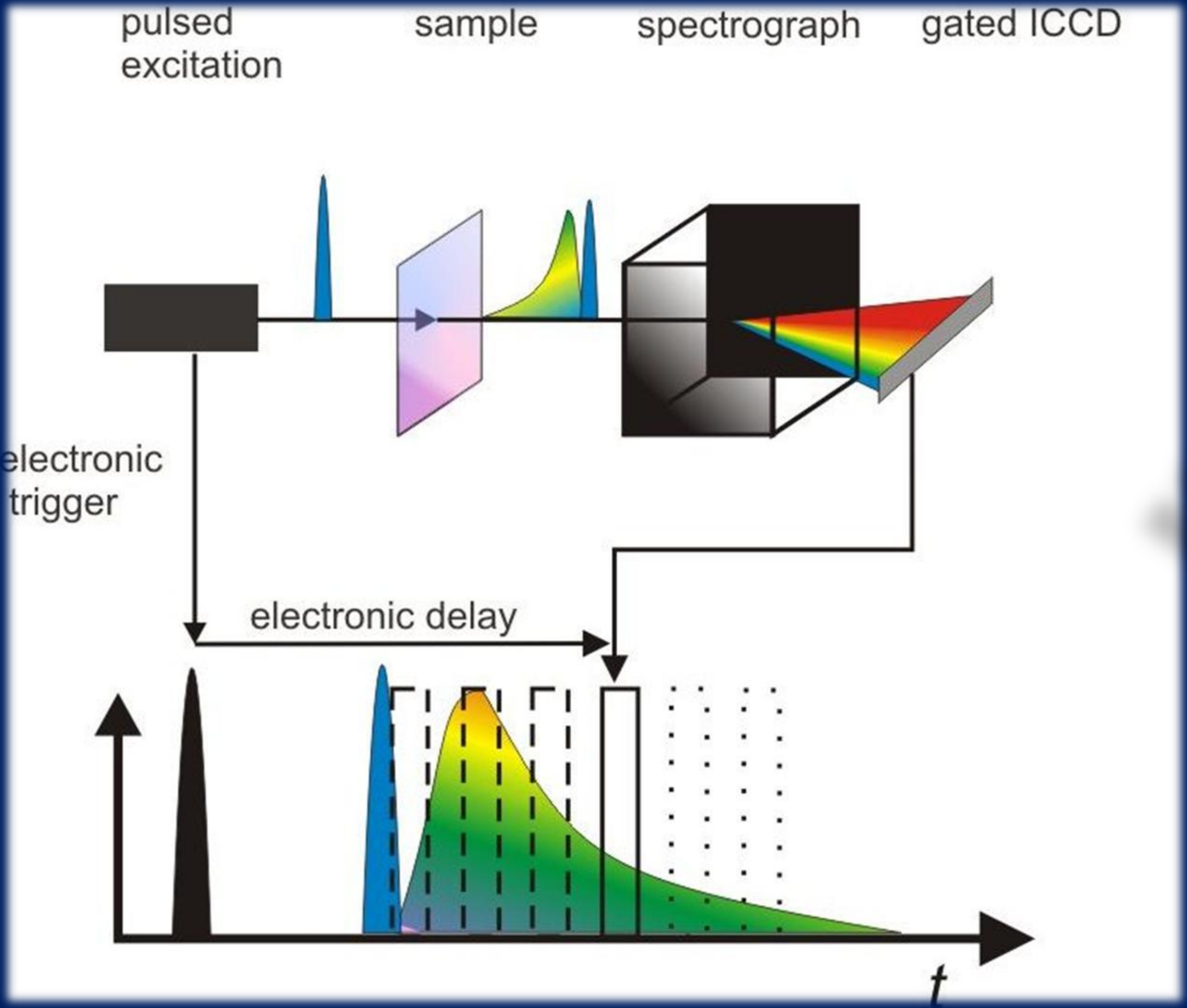
-Density of discrete states ?
-Phonon replica ?





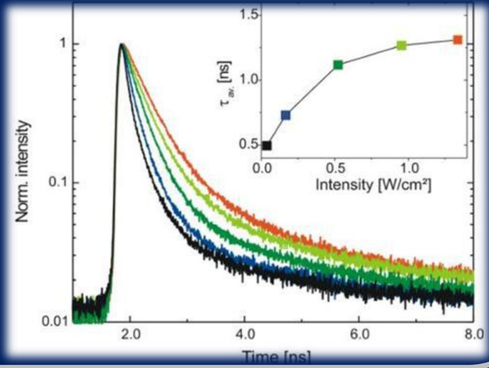


Time-dependent measurement

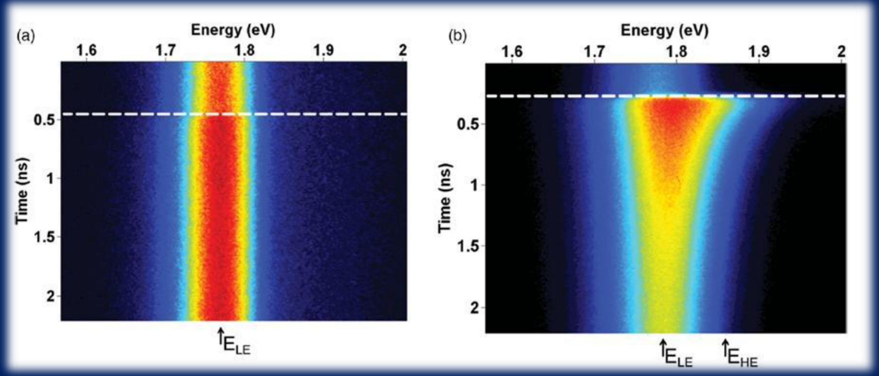


Conventional tr-PL

-Global Lifetime of the luminescence:



Streak camera spectroscopy:



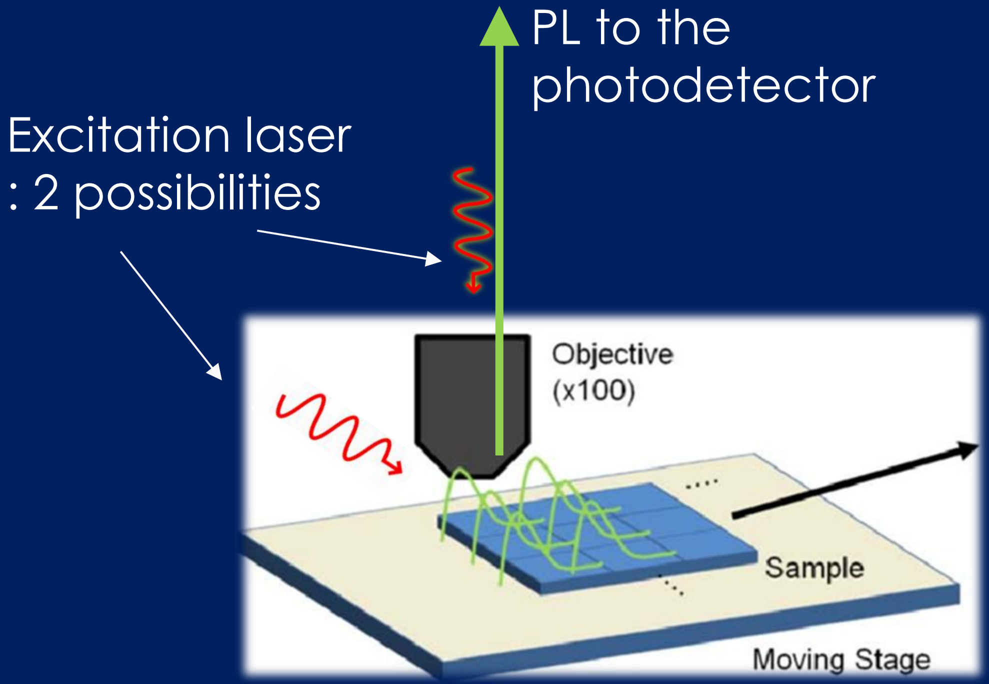
10K; 70 W.cm^{-2} 10K; 4000 W.cm^{-2}

Access to relaxation rates !

PL mapping

A powerfool tool to check samples inhomogeneity

Principle

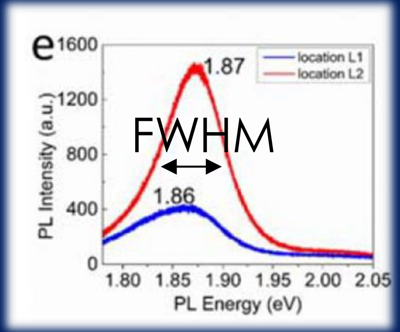


PL to the photodetector

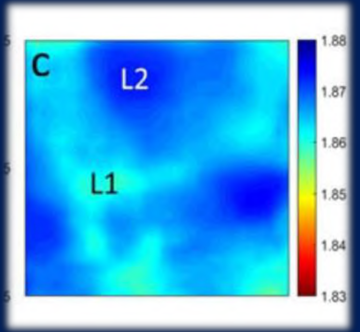
Excitation laser : 2 possibilities

A powerful technique but sometimes misunderstood (absence of low T)

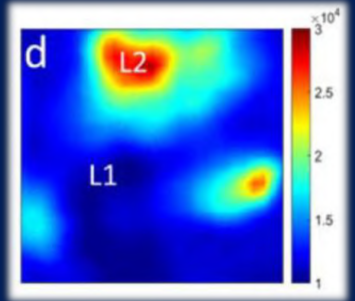
Samples & devices inhomogeneities



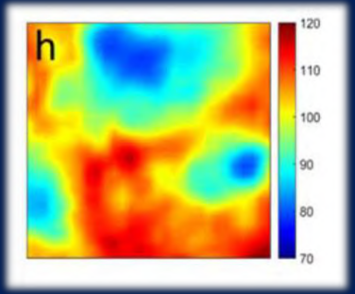
-PL spectrum at each pixel



-2D mapping for PL max energy



-2D mapping for PL intensity



-2D mapping for PL FWHM

Outline

I-Bandstructure of semiconductors, crystal defects and optical processes

-Bandstructures and semiconductors

-Crystal defects and their impact on optoelectronic properties

II-Characterizing light emission properties

-Photoluminescence

-Electro- & Cathodo-luminescence

III-Characterizing light absorption properties

-Absorbance measurements

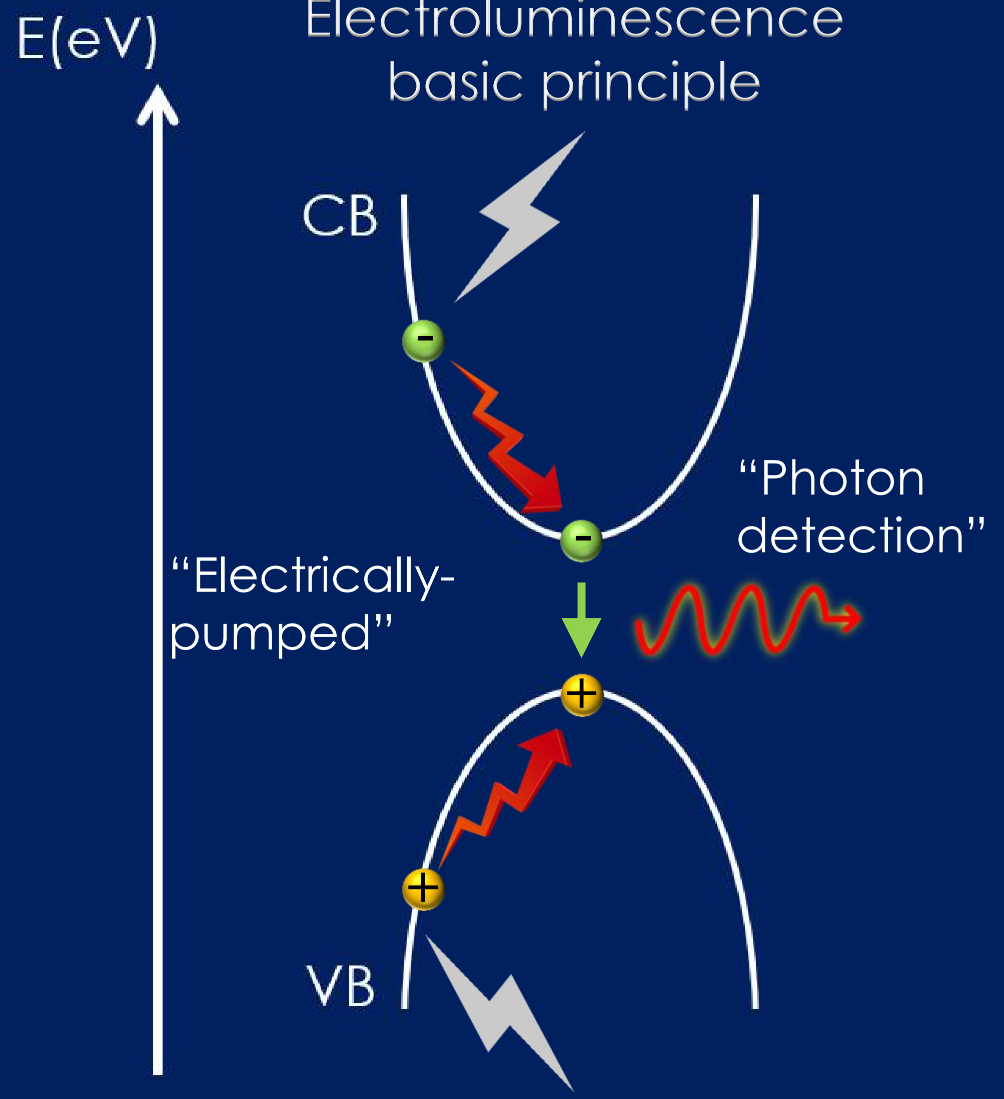
-Ellipsometry & Photo-current

IV-Toward single photons sources

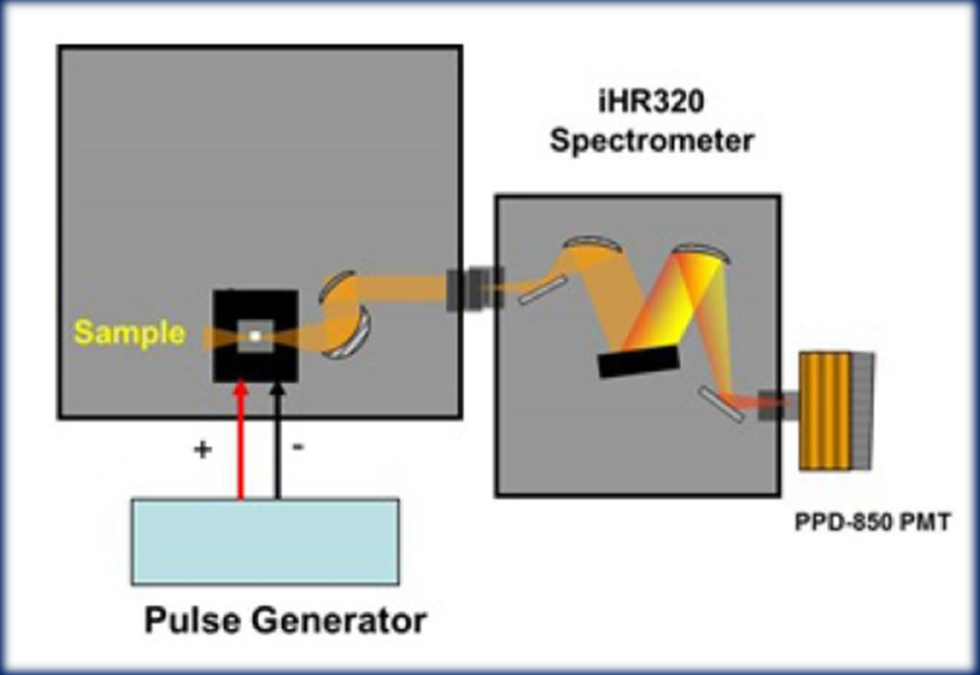
-micro-photoluminescence, g(2)

EL basic principle and setup

Electroluminescence basic principle



Electroluminescence basic setup



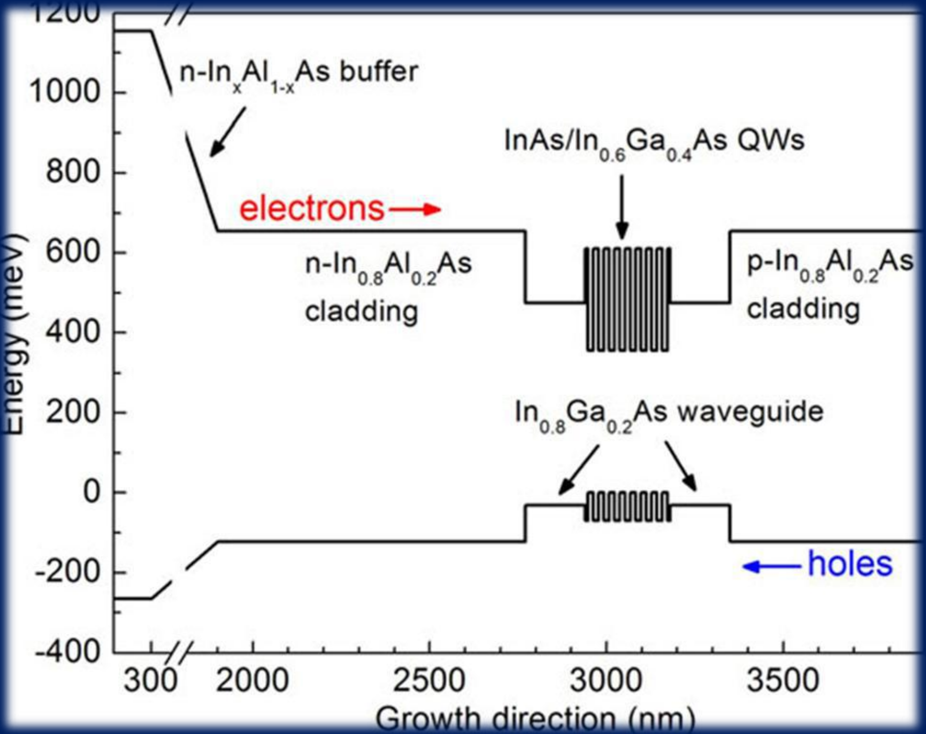
Similar to PL, but the semiconductor is now excited by a pulse generator

→ A larger density of injected charge carriers

The issue of carriers injection

Choosing the good stacking of materials

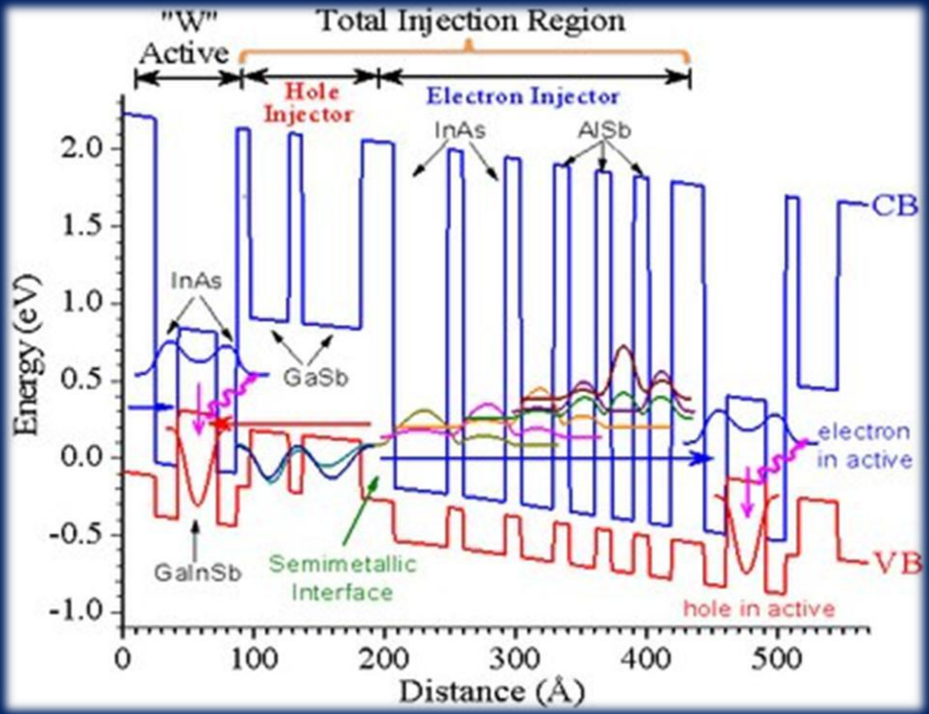
Ex : InP ridge laser



One should ensure that carriers are injected where the EL is expected

Managing the bias

Ex : QCL laser



Bias tends to make it even more complex

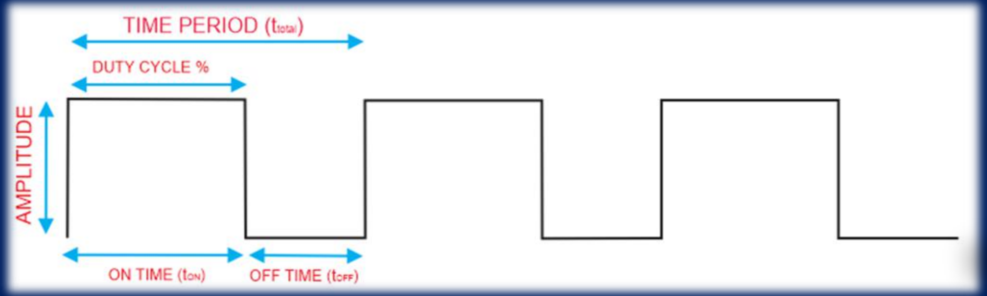
EL analysis is usually done on mature devices or materials stacks

Importance of the duty cycle

The pulse generator

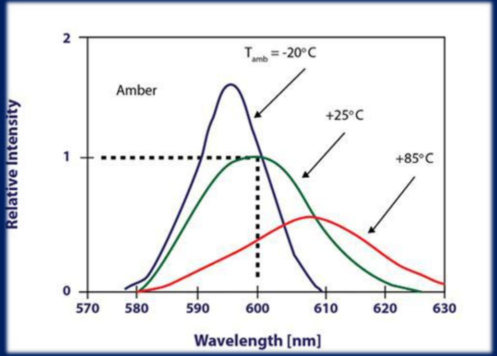
Continuous wave (cw) electrical pumping :

Pulsed electrical pumping :



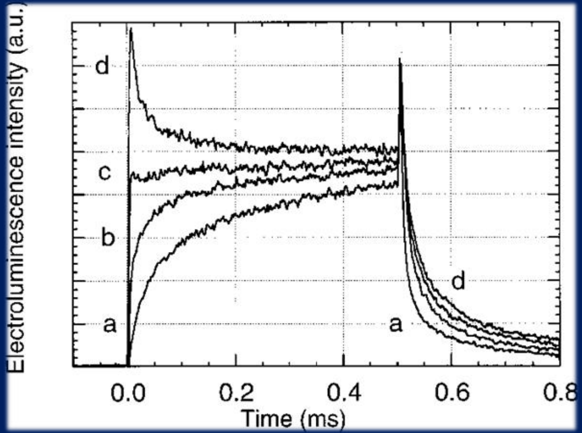
Thermal Management of the device

(Avoid degradation of devices du to heating)



Time-resolved analysis

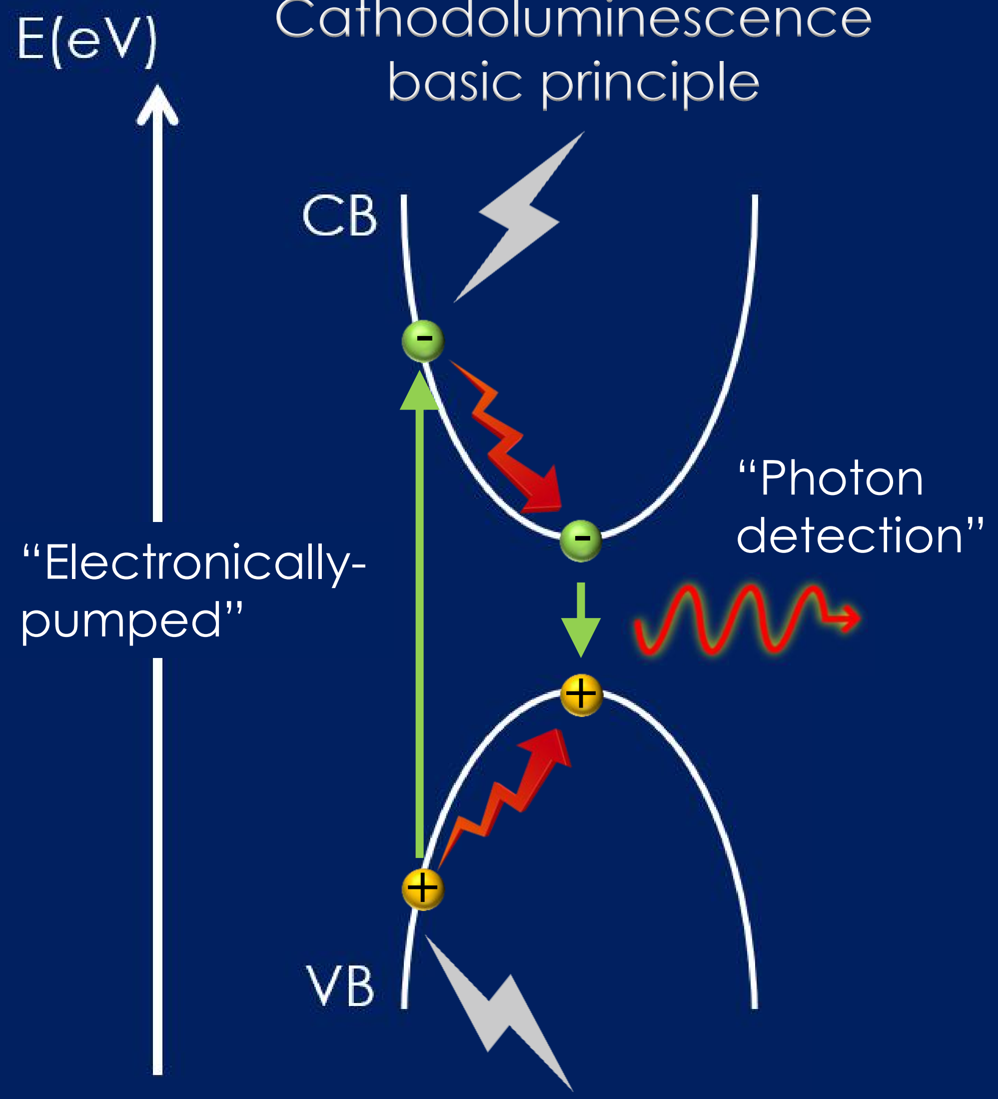
Transcient EL analysis of carriers injection



- The ultimate device should work in cw conditions
- The first step toward a laser device

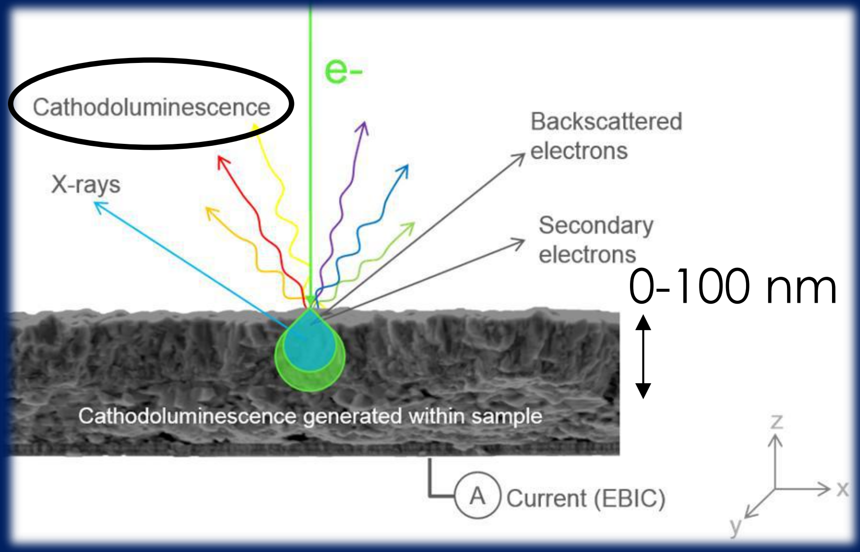
CL basic principle and setup

Cathodoluminescence basic principle



Electroluminescence basic setup

Cathode-Ray tubes e- (1,5 to 25 kV)



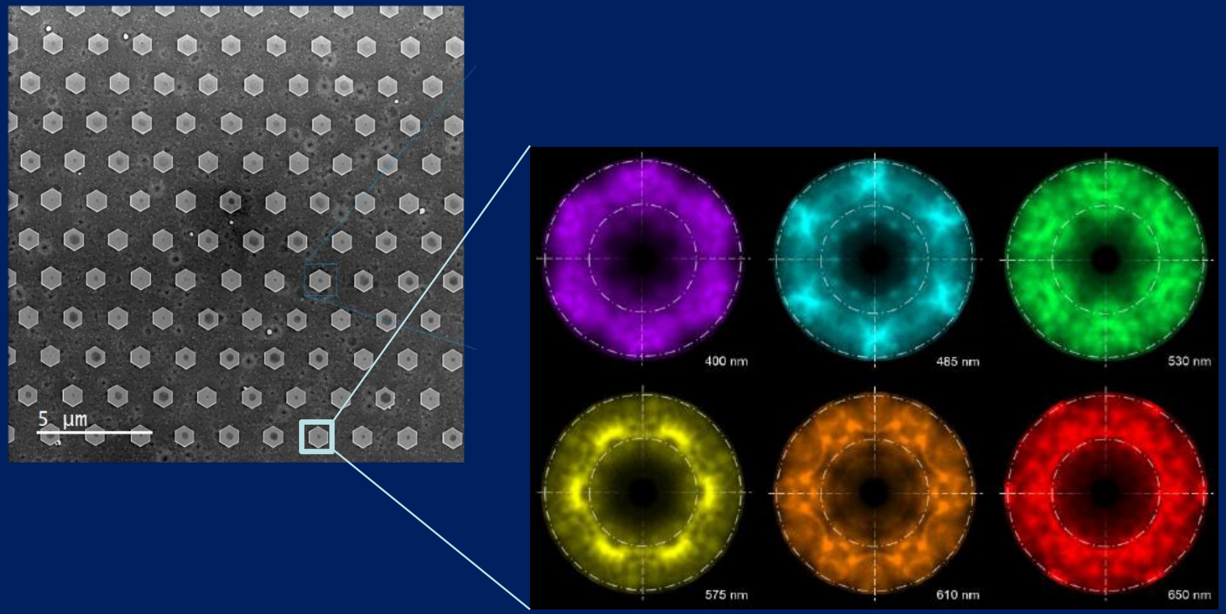
Similar to EL, but the semiconductor is now excited by an electron beam

➡ A much more complex experiment than EL and PL

Promises and limits

Promises

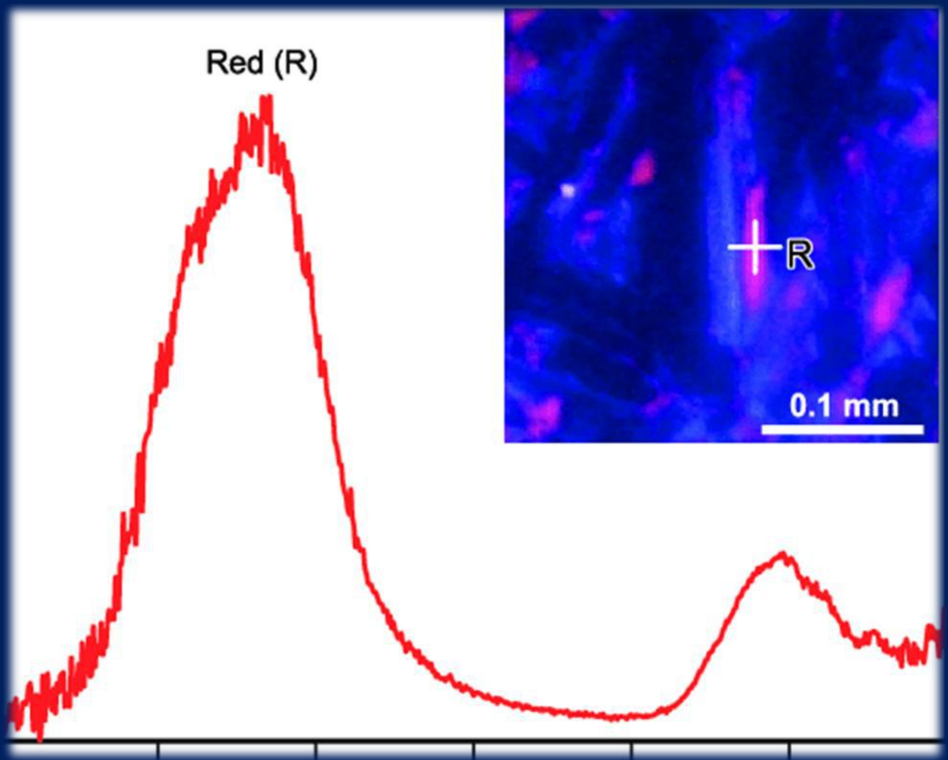
Ex: III-N nanopillars



- Low-T, time-resolved, and mapping available, with a high spatial resolution, and variation of the depth

➡ Interesting for localized defects, and sub-micronic nanostructures

Limit : An excitation spectroscopy



➡ Mapping gives the coordinate of excitation, but the whole CL on the sample

Intermediate conclusion

Optical processes

- Understanding optical processes = understanding time constants

Photoluminescence

- Looks like a simple experiment, but requires deep understanding of the processes (T°C, Power, tr-).
- Constant competition between radiative and non-radiative recombination channels

Electroluminescence

- A simple experiment, on mature samples/devices
- Importance of the pulse generator

Cathodoluminescence

- A complex experiment, adapted for localized spectroscopy
- An excitation spectroscopy

Outline

I-Bandstructure of semiconductors, crystal defects and optical processes

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-Crystal defects and their impact on optoelectronic properties

II-Characterizing light emission properties

-Photoluminescence

-Electro- & Cathodo-luminescence

III-Characterizing light absorption properties

-Absorbance measurements

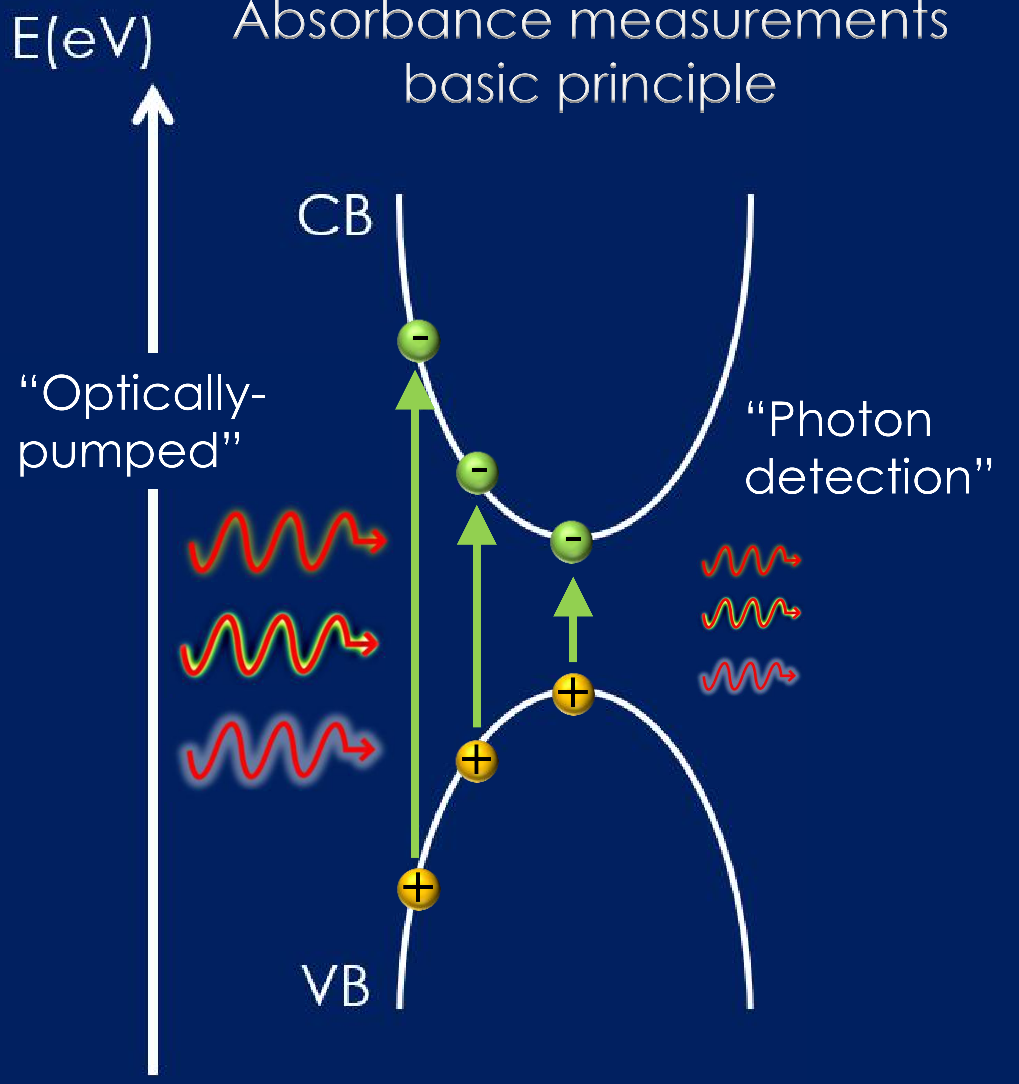
-Ellipsometry & Photo-current

IV-Toward single photons sources

-micro-photoluminescence, g(2)

Absorbance basic principle and setup

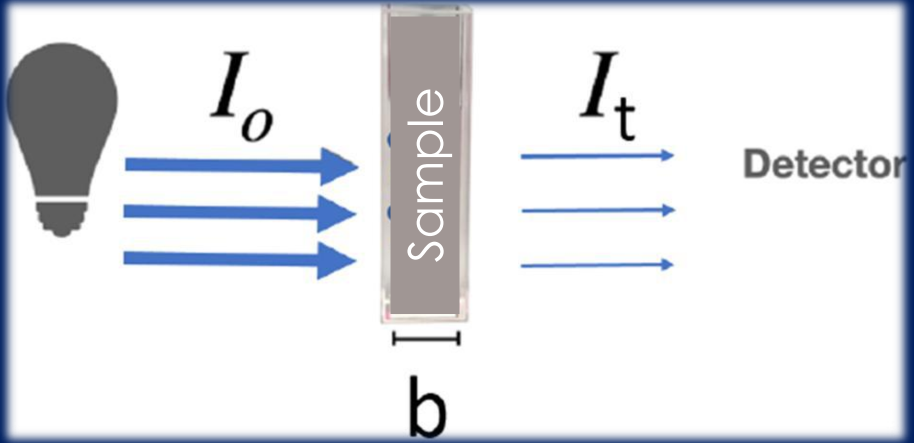
Absorbance measurements basic principle



Absorbance basic setup

-Light sources :
→ Broadband light sources
→ Tunable laser

-Detectors:
→ conv. photodetector



The measurement gives the Absorbance :

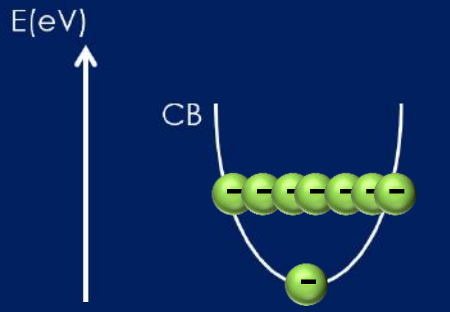
$$A = -log_{10}(\frac{I_t}{I_0})$$

Absorption coefficient is then inferred :

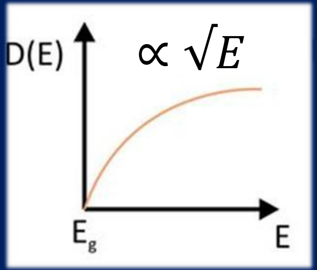
$$\alpha = {}^{A}/_{b} \qquad (\mathrm{cm}^{-1})$$

Useful informations about absorption

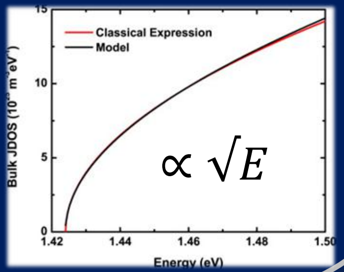
Joint density of states



-<u>Bandstructure</u> : different possible states possible for each energy

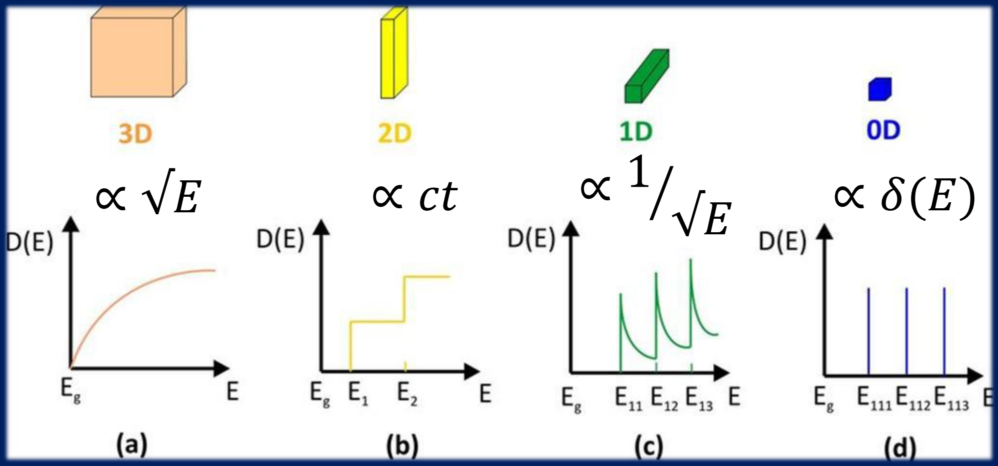


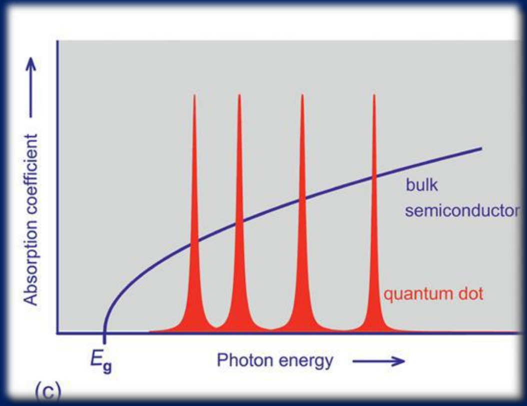
-<u>Density of states DOS</u> : density of possible states /energy /volume



-Joint <u>Density of states JDOS</u> : density of possible optical transitions /energy /volume, at constant k

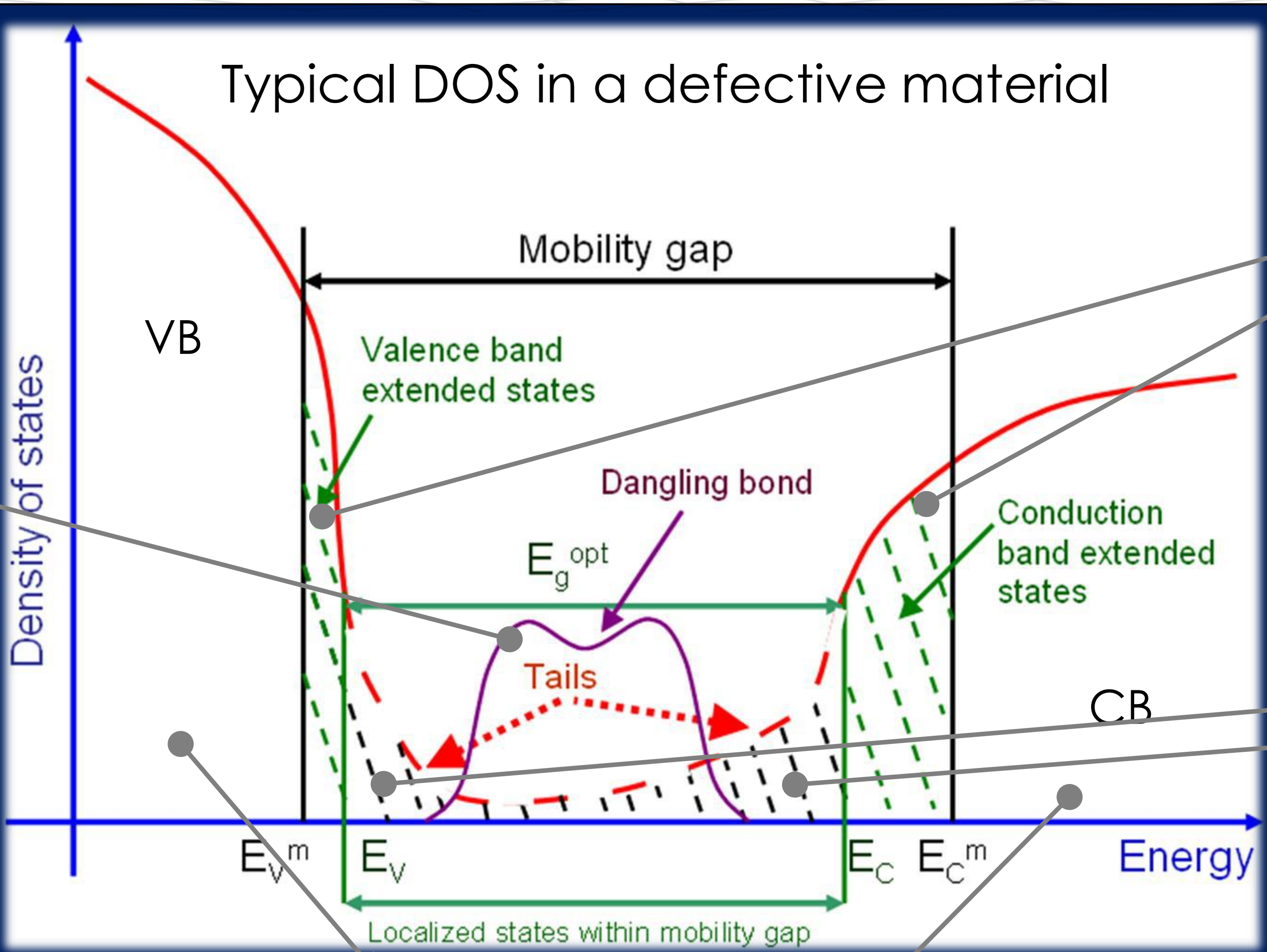
JDOS and absorption





Absorption ~ screenshot of the JDOS

Promises of absorbance measurements



Dangling bonds defects

Potential fluctuations (e.g. alloying)

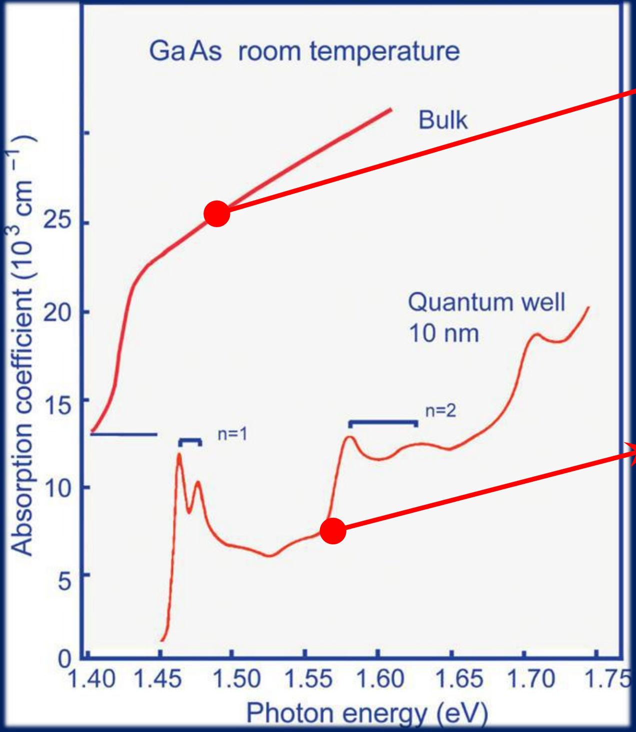
Localized states (traps) or quantum structures

Bulk material

In real conditions, mid-gap states are hardly accessible with absorbance (density, optical activity)

Absorption : a bunch of useful information

Ex : Quantum confinement



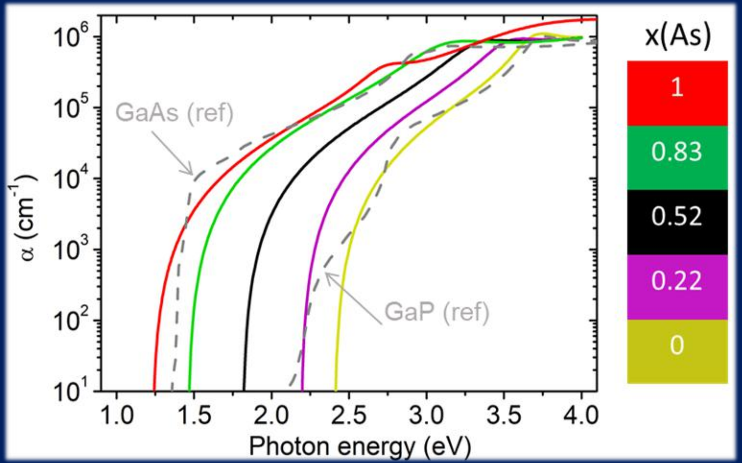
Typical $\sqrt{E}$ bulk-like evolution

Typical step structure →quantum confinement

Allows to identify quantum confined systems

Ex : alloying

$GaAs_xP_{(1-x)}$

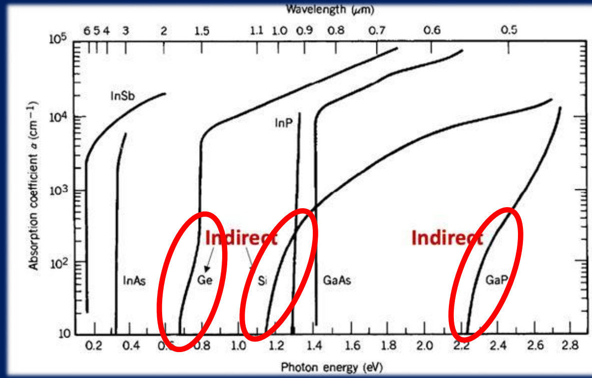


Ex : Direct/indirect bandgap

Absorption edge :

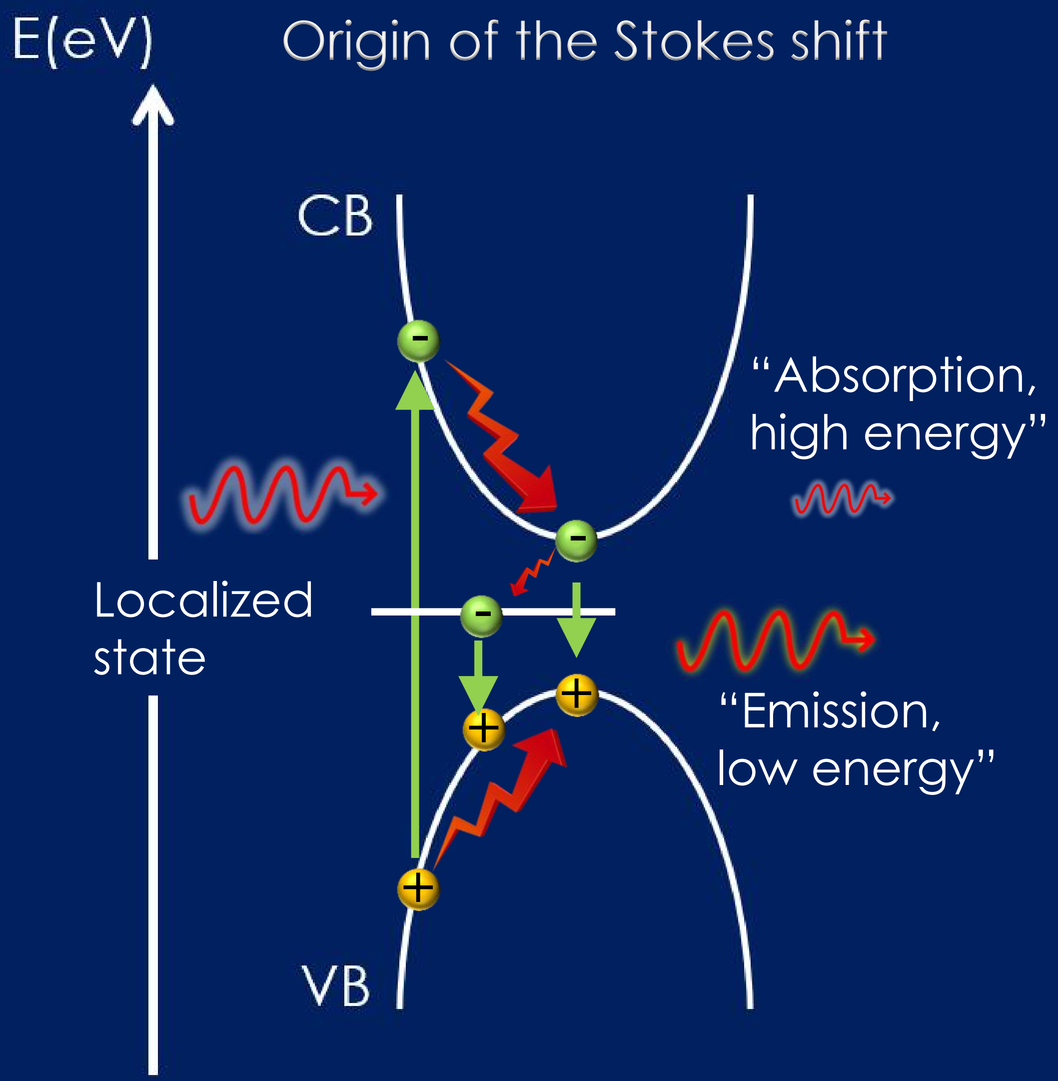
-sharp for a direct bandgap

-smooth for an indirect bandgap



The Stokes Shift

Origin of the Stokes shift

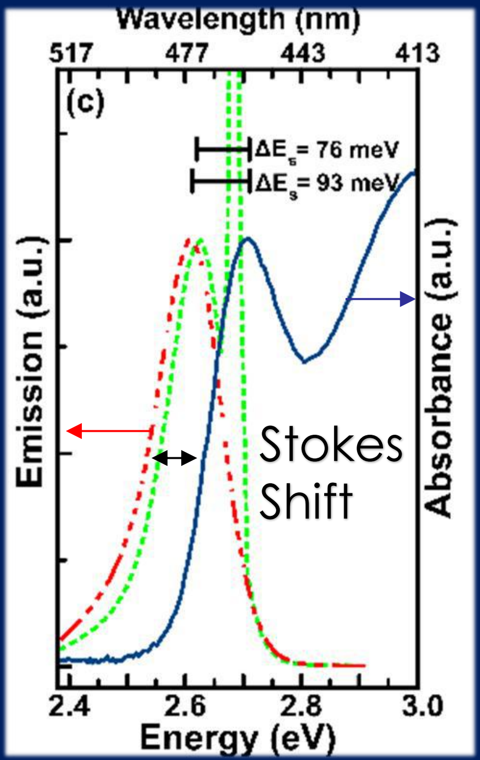


Localized state

"Absorption, high energy"

"Emission, low energy"

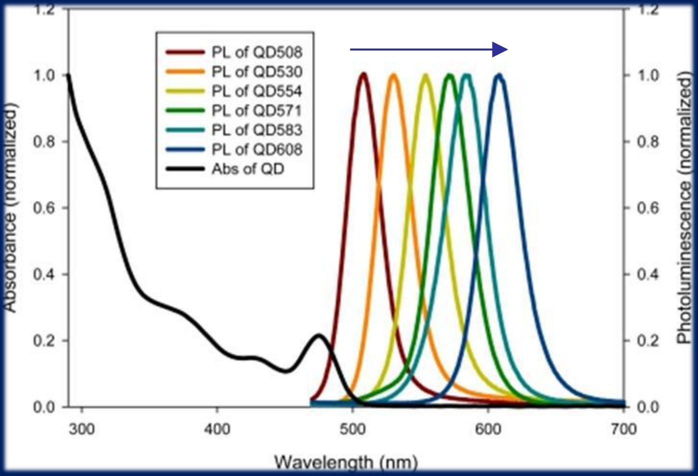
Usual situation



Max of the PL = absorption edge

Strong Localization

Increased localization



Stokes shift is a measure of the localization

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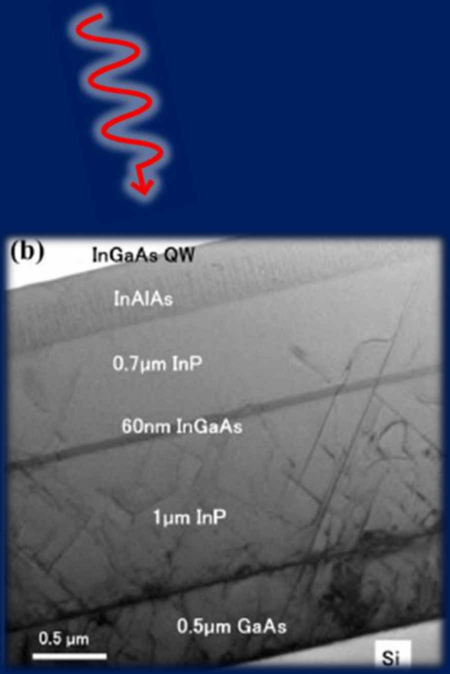
Motivations

The stacking issue

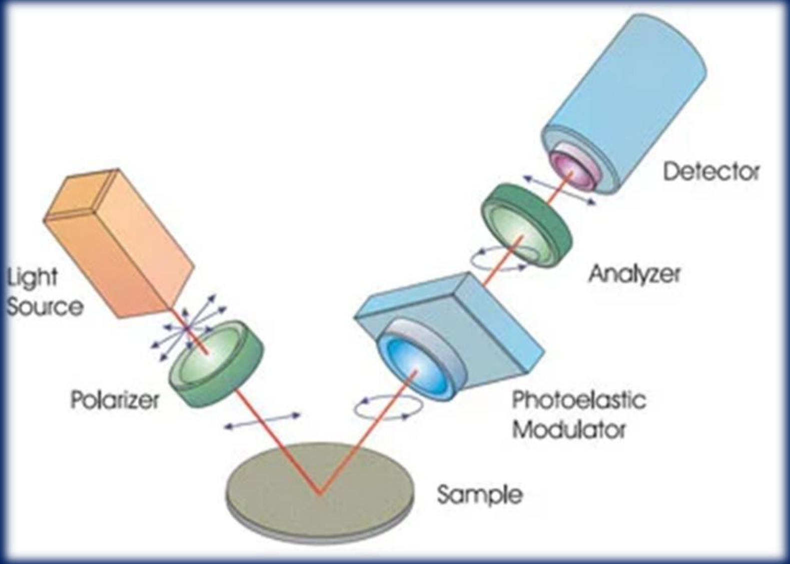


-Different layers with different bandgaps and n,k optical constants

-Optical constants (n,k) of the individual layers ?

Global absorption of the whole sample can only be determined

Ellipsometry

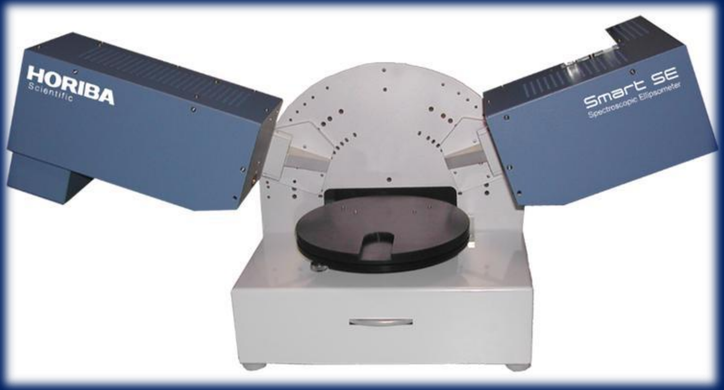


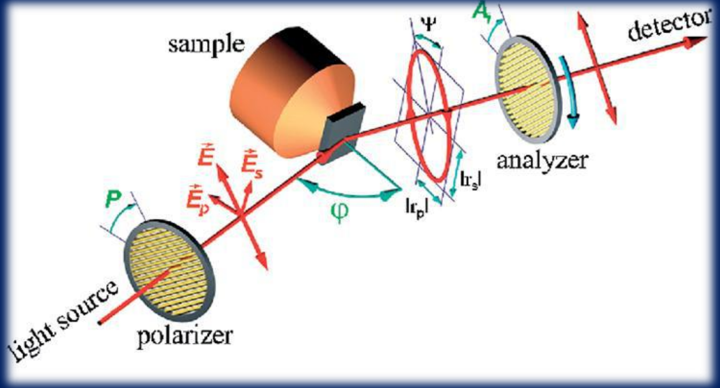
Analysis of the change of the polarization of light during the reflection on the sample

A very powerful technique

The method

Measurement



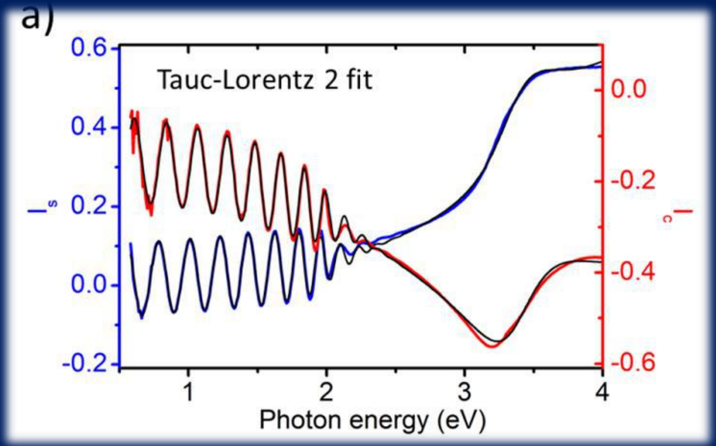


Measure of I_s and $I_c = f(\Psi, r_s, r_p)$

Fitting

→the trickiest part of the job

→Needs to assume a model

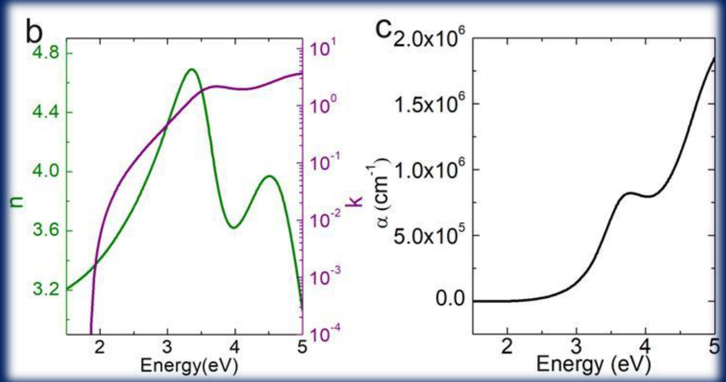


Optical constants

For each individual layer :

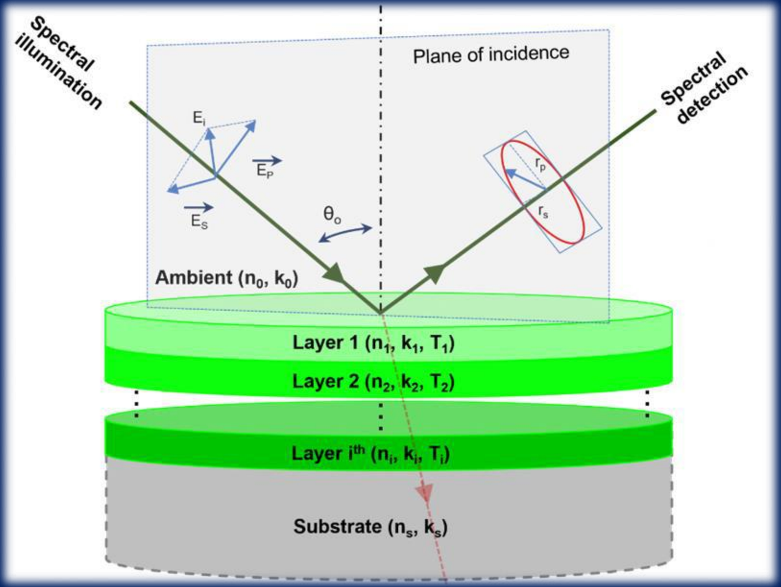
- n, optical index
- k, extinction coefficient

α, absorption coefficient



Applications

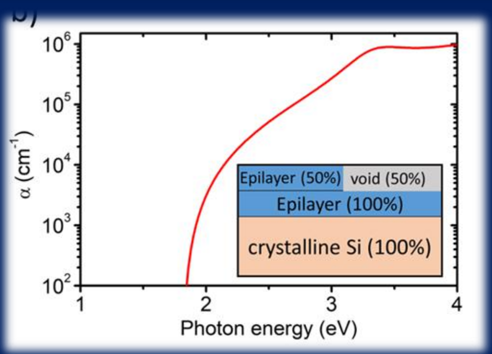
Optical constants and thicknesses



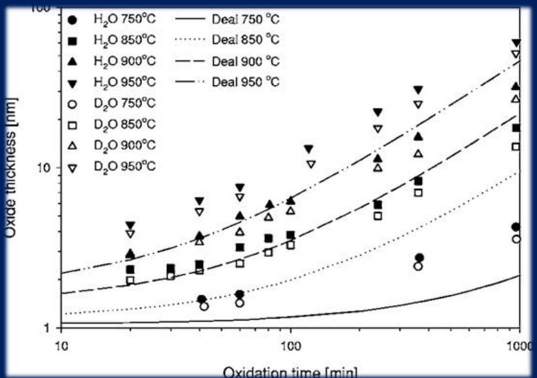
Systematic determination of optical constants and thicknesses

Roughness of surfaces and interfaces

→Roughness of surfaces and interfaces is a fitting parameter

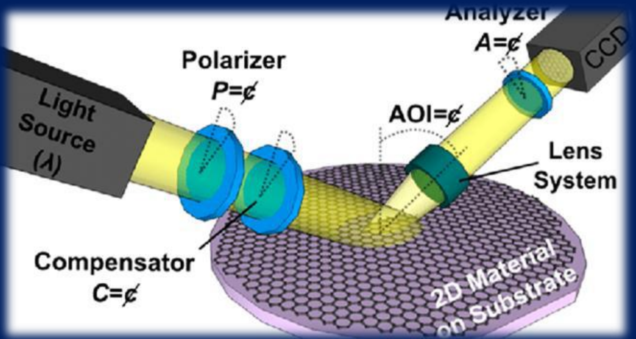


Oxidation of surfaces



→Thicknesses as low as 1 nm can be detected

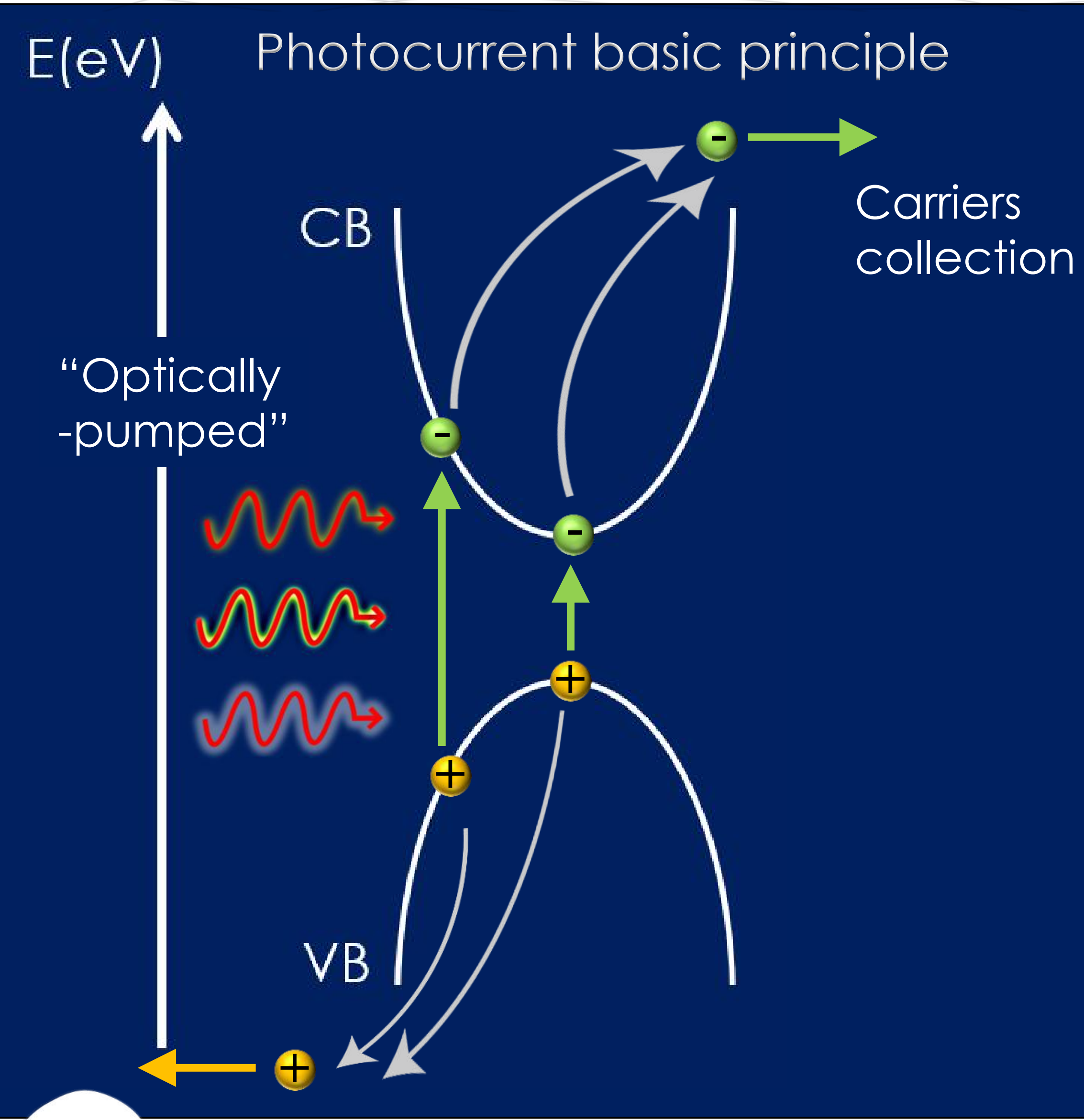
Optical constants of 2D materials



→Advanced applications (mapping)

PC basic principle and setup

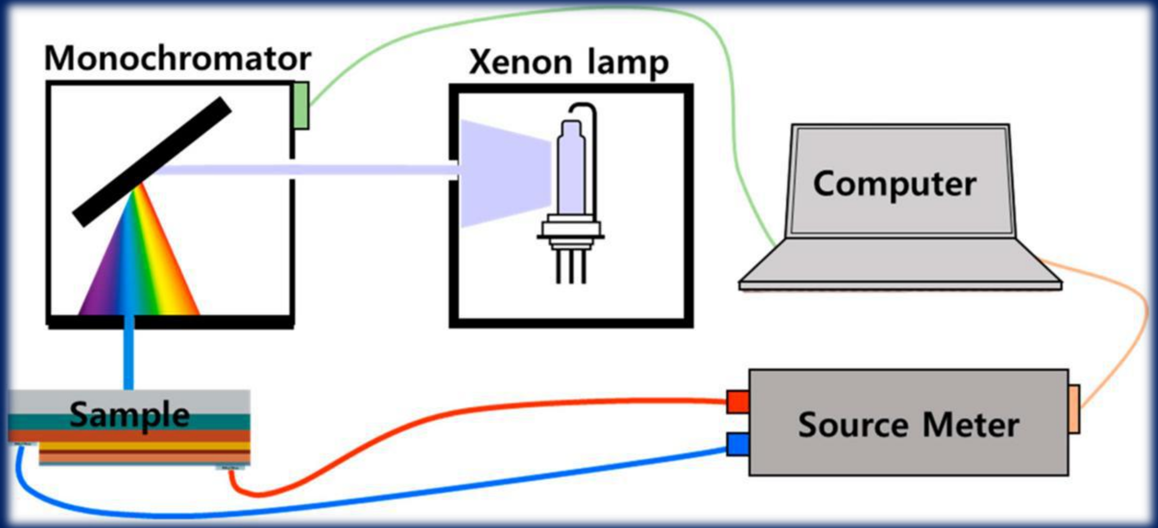
Photocurrent basic principle



Photocurrent basic setup

Sources :

- Broad band light source + monochromator
- Tunable lasers

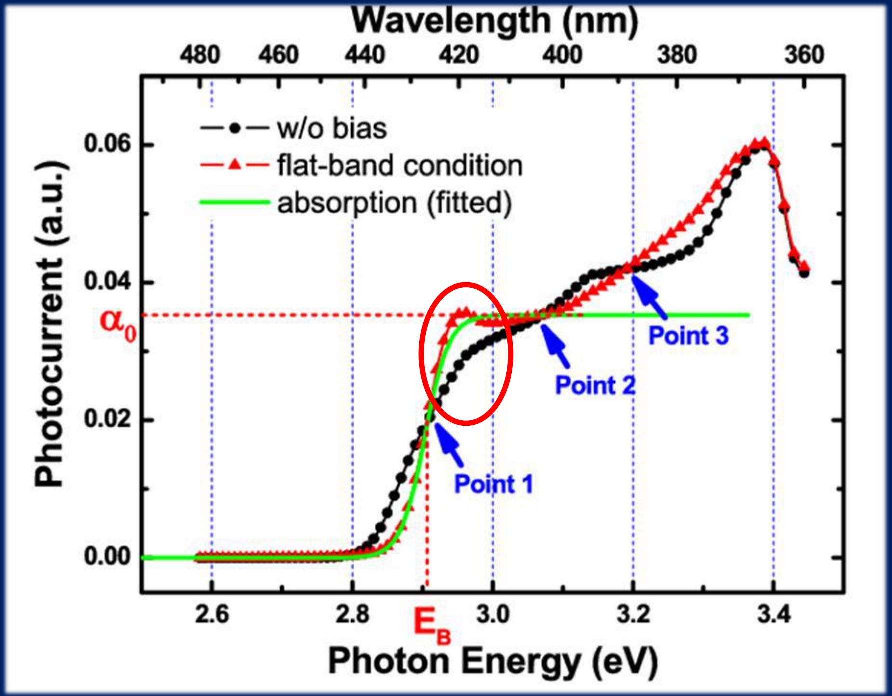


Collection of electrical signal

➡ Evaluation of the absorption + photo-generated carriers extraction efficiency

Applications

Analysis of carriers injection/collection

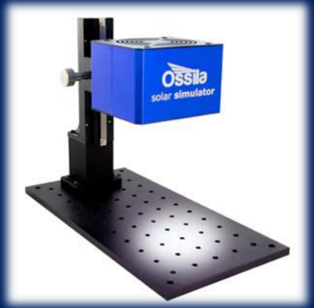


Ex : InGaN/GaN LED

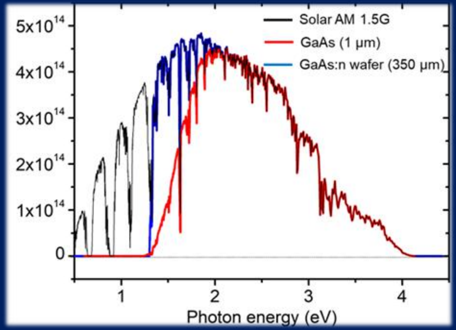
→ Different carriers collection w or w/o bias, selective contacts, …

Photovoltaic applications

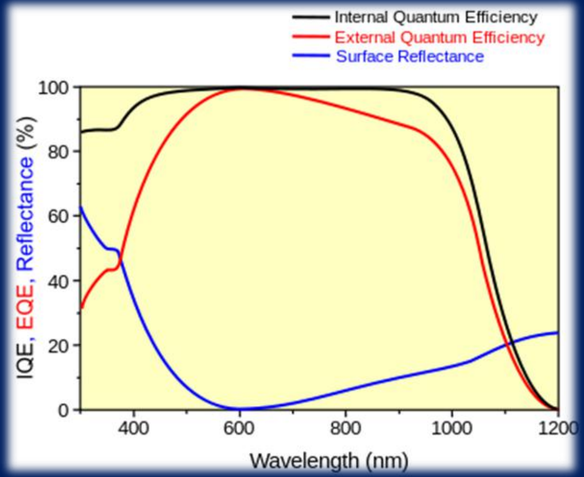
- Solar AAA simulator



- Sample absorption



- Evaluation of the ability of the solar cell to generate photocurrent from the solar spectrum



→ EQE, IQE

Intermediate conclusion

Absorbance measurements

- Measuring the absorption ≈ measuring the JDOS
- Although defects theoretically contribute to absorption, not easy to detect experimentally
- Absorption useful for determining quantum confinement, alloying or band type (direct/indirect)
- Stokes Shift (PL & absorption) characterize the localization

Ellipsometry

- A powerful tool to determine optical constants of materials stacks
- Also interesting for roughnesses of surfaces/interfaces, oxidation, or 2D materials

Photo-current

- Allows to identify carriers collection issues
- Allows to identify specific features due to sunlight irradiation

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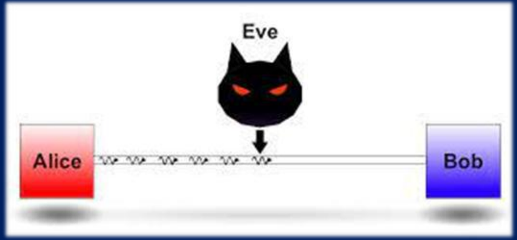
Single photon emitters

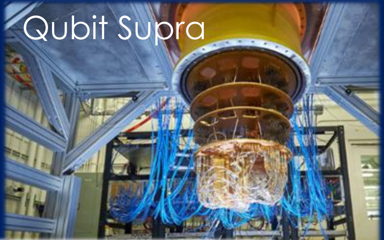
Quantum communications

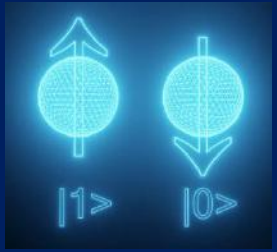


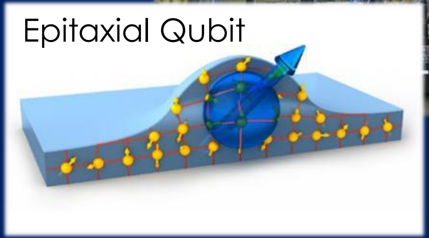
- Quantum cryptography, Quantum key distribution

Quantum computing

- Qubit computing : fast, powerful

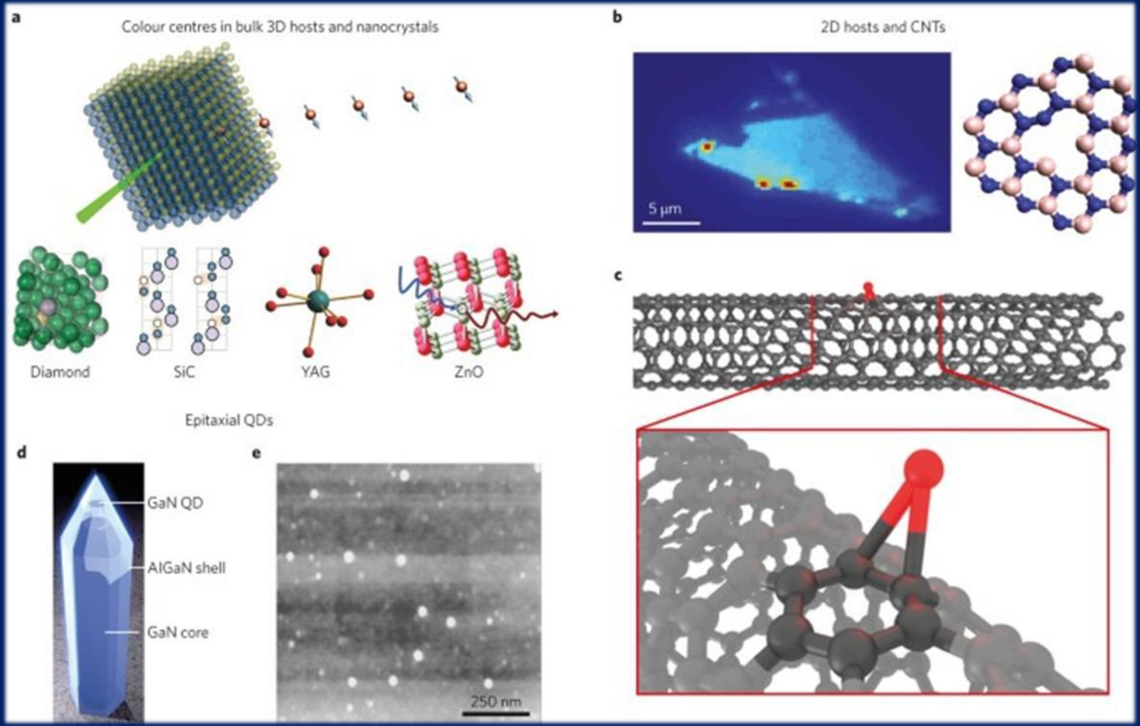






Single photon sources

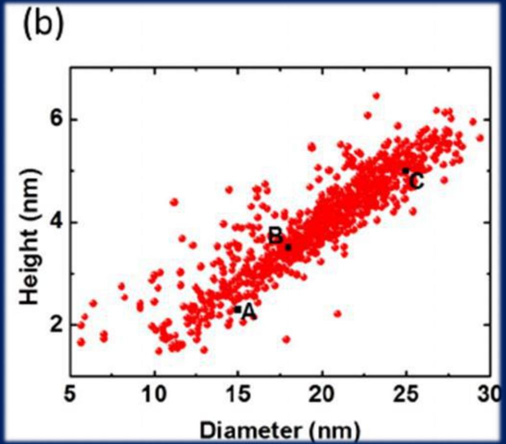
- Quantum properties of single photons are of great interest for QT

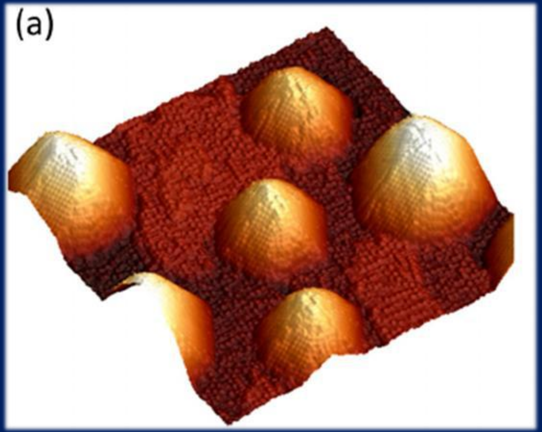


Many nanostructures were proposed for single photon emitters

Individual emitters

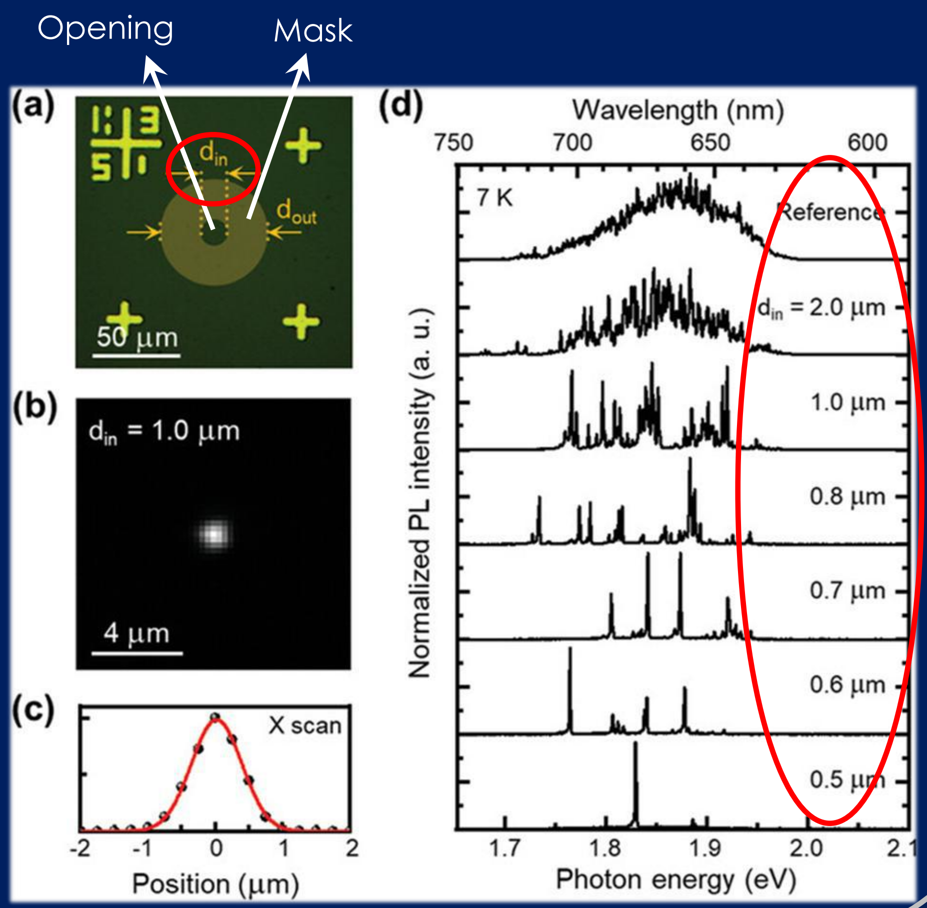
Structural inhomogeneities of QDs





Structural inhomogeneities
→inhomogeneities of Energy levels

Inhomogeneous vs homogeneous broadening

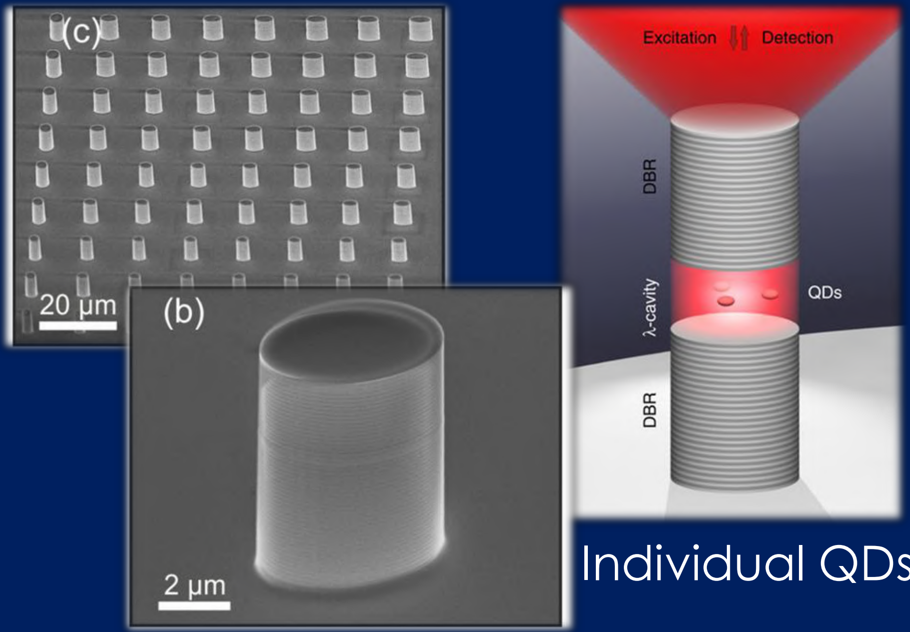


Emitting window reduction to adress single emitters

Micro-Photoluminescence

Individual emitters physical separation…

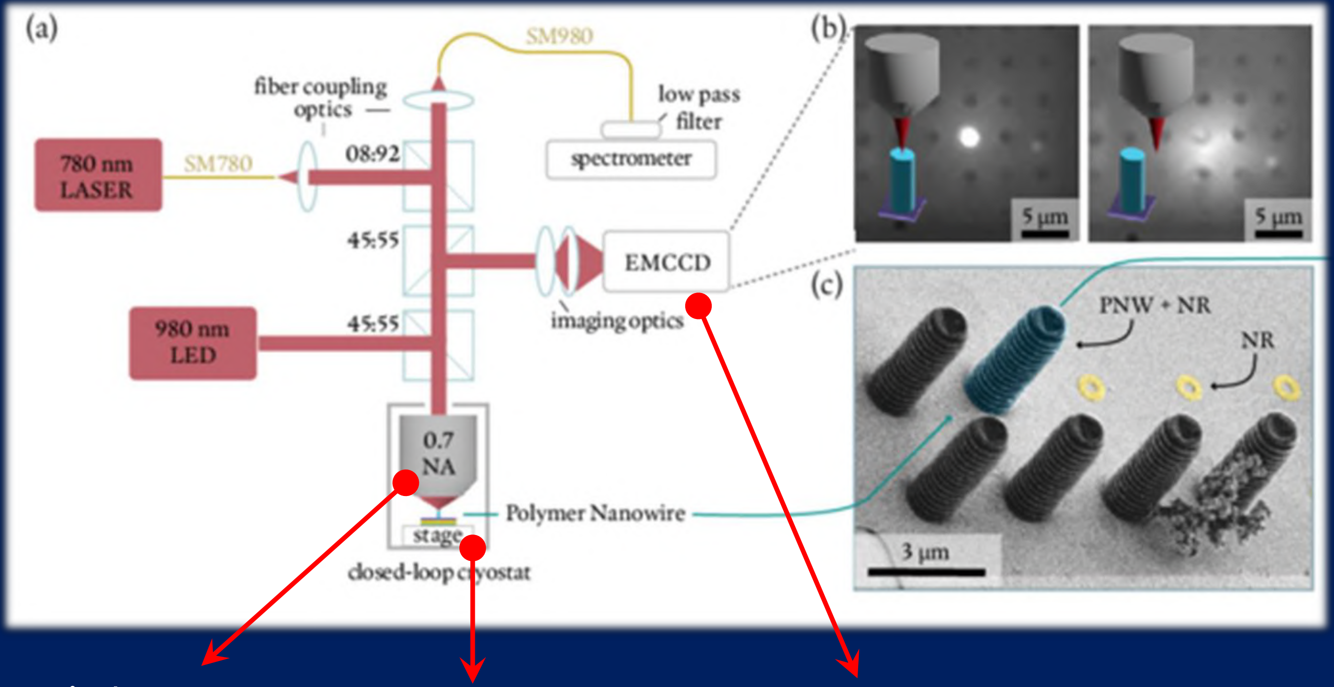
µ-pillars array



Individual QDs

Many different strategies to isolate individual emitters (pyramids, NWs…)

… and micro-Photoluminescence setup



High magnification lens

X-Y micro-positioning stage

Imaging optics for micro-positioning control

The single photon issue

About time statistics : How can we ensure that single photons are emitted ?

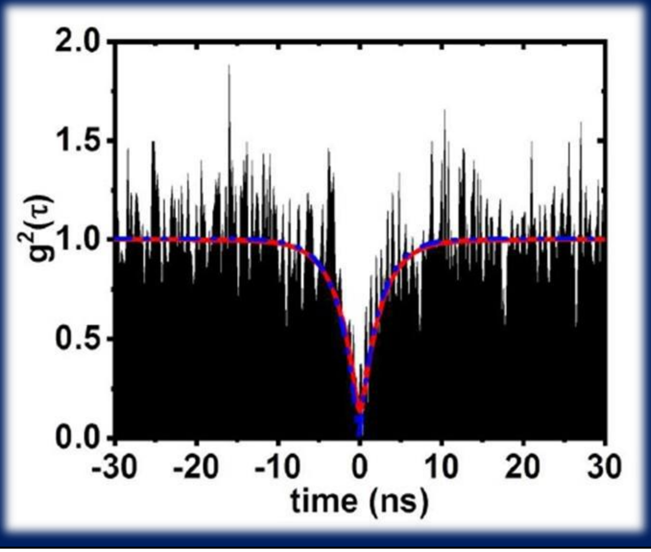
- Temporal average is not sufficient :

10 photons/s ⇔ 1 photon every 0,1 s

Autocorrelation in intensity g²(τ) :

-Probability of emitting a photon at time t, when a photon was emitted a time t+ τ

$$g^{(2)}(\tau) = \frac{\langle n(t)n(t+\tau)\rangle}{\langle n(t)\rangle^2}$$

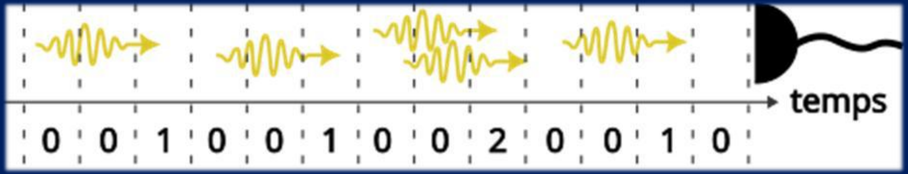


- *For a single photon emitter,* g²(0)=0.

Measurement of the $g^{(2)}$

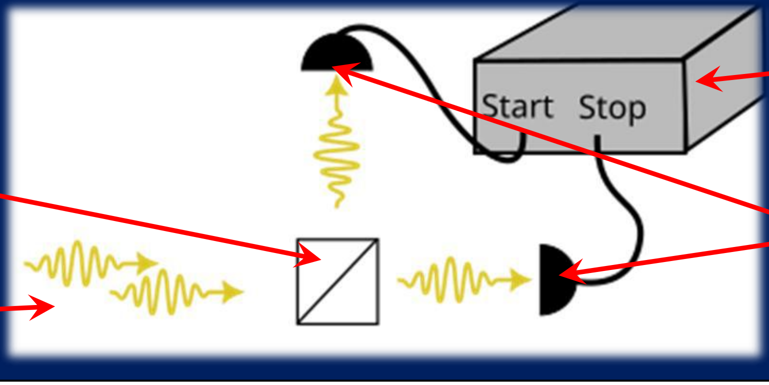
How can we measure experimentally the $g^{(2)}$?

- To measure $g^{(2)}$, one has to count photons



Avalanche PhotoDiode (APD) can detect only one photon at a time, and convert it into electrical signal

- The experimental setup looks like :



Correlator

Beam splitter

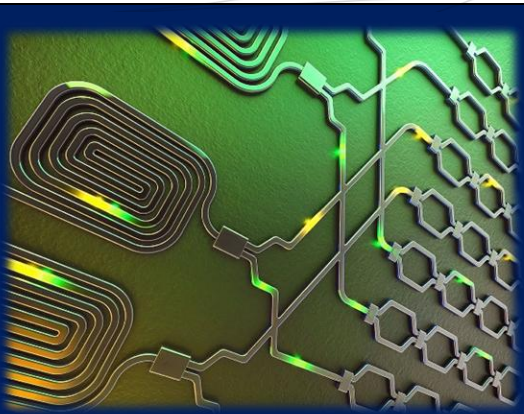
APDs

Photons Emitted from sample

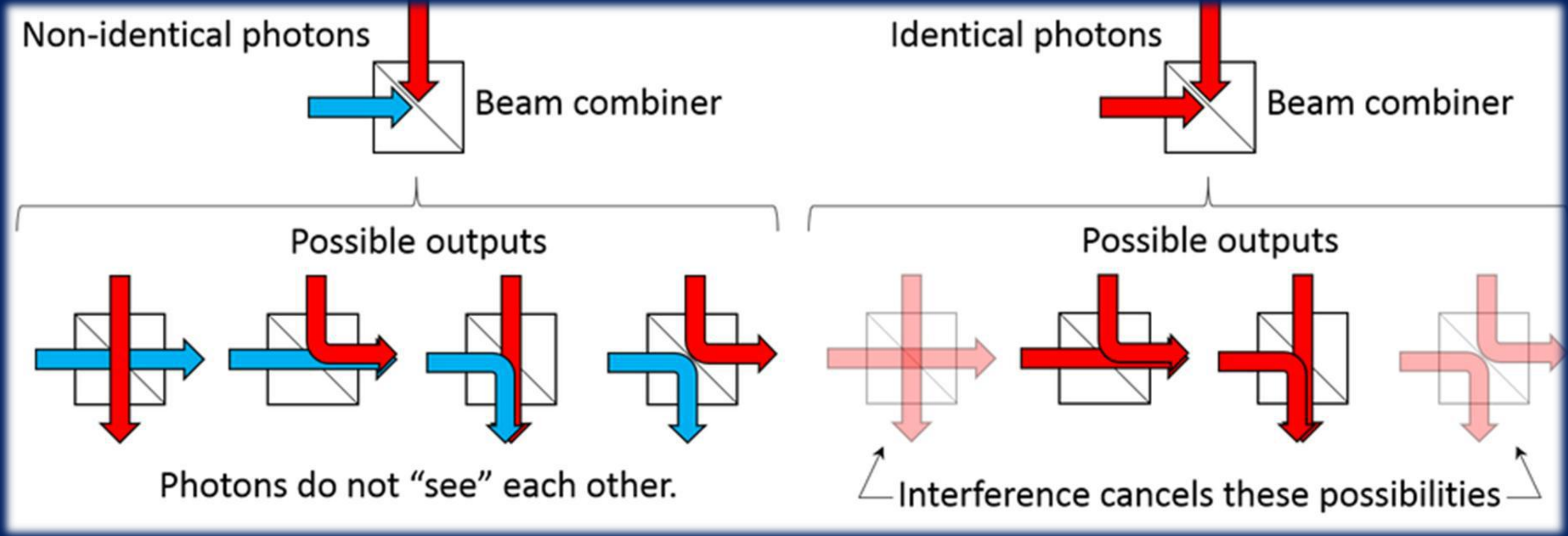
Indistinguishable photons

Motivations

- Quantum properties of 1 photon are interesting
- Quantum properties of a 2 photons - system are much more exciting
- Quantum states in a 2 photons-system : a fundamental step toward quantum technologies



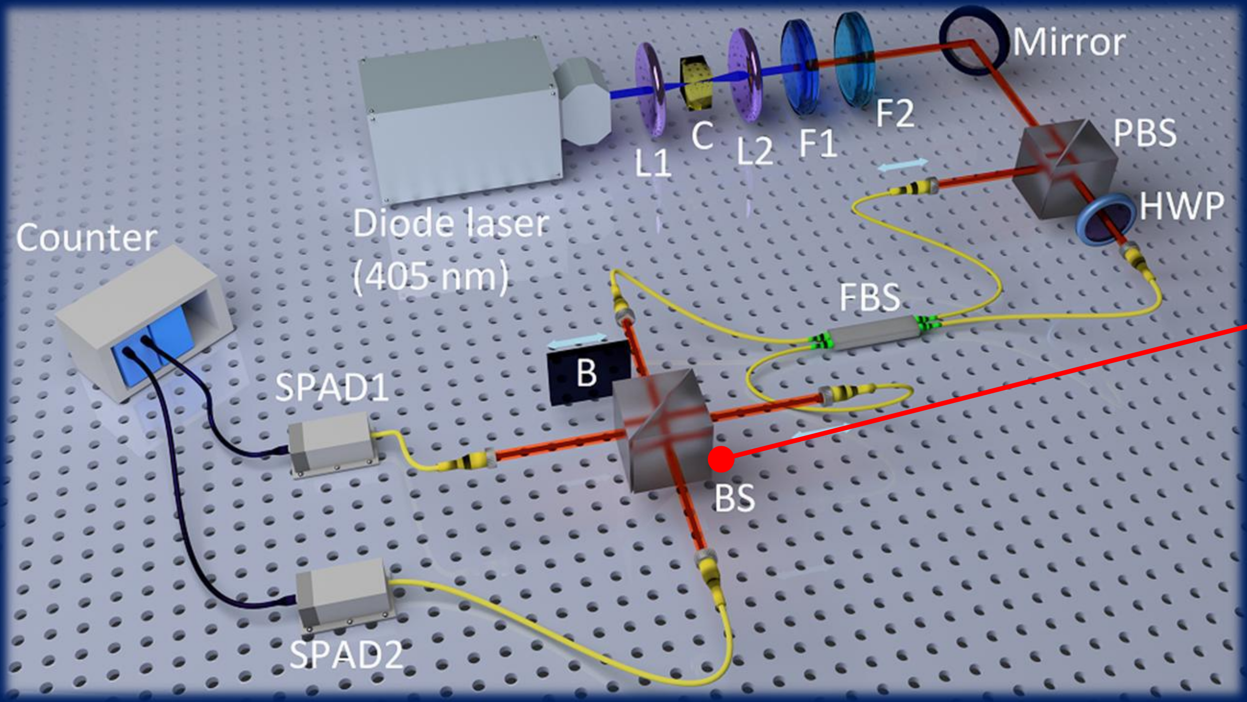
Properties of indistinguishable photons

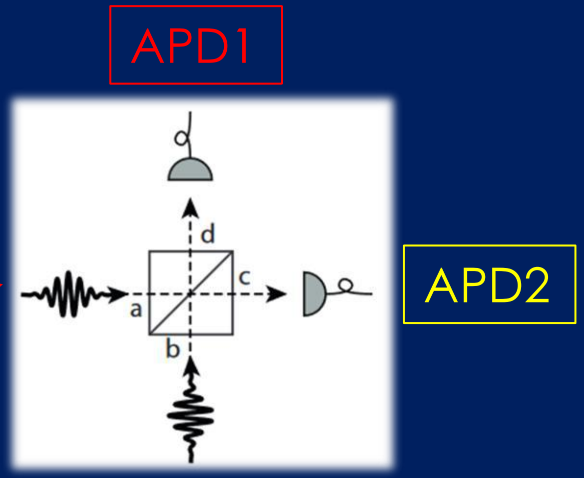


- Hong-Ou-Mandel (HOM) effect = quantum interference

Measurements of the HOM effect

Similar setup than the $g^{(2)}$ but needs for two input signals





If pairs of photons arrive always on the same photodetector, photons are indistinguishable

Intermediate conclusion

Single photons sources

- A large variety of nanostructures are now available for single photons sources, especially point defects
- $g^{(2)}$ experiments (correlation) are commonly implemented in Labs today.
- The control of quantum properties of 2-photons systems become a hot topic for the development of quantum technologies

General Conclusion

- Understanding optical processes in materials = understanding time constants and bandstructure
- Crystal defects in epitaxial materials have a huge impact on optoelectronic properties, not always detrimental
- (Electro-)optical characterizations of epitaxial materials provide number of useful information on crystal structure and bandstructure
- This information is crucial for the development of novel materials and devices, in the field of photonics, Energy applications or quantum technologies

For anyone wanting some bibliography about one of these topics, please contact me directly at : charles.cornet@insa-rennes.fr

Thanks for your attention, questions ?